UNIVERSITA' DEGLI STUDI DI GENOVA

POWERTILLERS AND SNAILS FOR HUMANITARIAN DEMINING: PARTICIPATORY DESIGN AND DEVELOPMENT OF A LOW-COST MACHINE BASED ON COMMERCIAL AGRICULTURAL TECHNOLOGIES

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A thesis submitted for the degree of Doctor of Philosophy in the Faculty of Engineering of the University of Genova, Italy

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20th of May 2008

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I hereby certify that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due to acknowledgment has been made in text.

Genova, 20/5/2008

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Unless otherwise acknowledged all pictures are from the author.

Abstract

There is increasing consensus on the fact that landmines heavily affect the development of contaminated countries and that mine action activities need to be integrated into general development initiatives. There is also general acknowledgment that machines available on the humanitarian demining technology market are often too costly and poorly locally sustainable: only few are actually employed in the field and are often down for maintenance, waiting for spare parts or for experienced technicians to fix them coming from abroad.

The thesis summarises several topics in the domain including an analysis of humanitarian demining technology market, the investigation into the relationship between science and technology and human development, a review of participatory tools in use in mine action and in other sectors, and introduces a new integrated approach to the design of *simpleffective* demining technologies. The methodology, called the Snail System, originally developed in the context of this work, is very similar to the one recently proposed by Bernard Roth in his paper Design Thinking, published at International Mechanisms and Machine Science Conference, held in China in 2006. Within the thesis the snail system is applied to the design, development, manufacturing and preliminary test of a simple modular machine for assisting manual demining operations in Sri Lanka, through ground processing. The tractor unit and the ground processing tool are chosen in the agricultural machines domain, so that to assure the full consistency with the local expertise and habits. Cost and sophistication minimisation is primary objective of project. While the tractor unit is developed around a powertiller, small two wheeled tractor largely used in all South East Asia, the ground processing tool is designed taking into consideration rules generally followed into the design of primary tillage tools. The ground processing tool prototype has been developed and preliminary tested in Jordan, with the support of Norwegian People's Aid (NPA) Jordan and the University of Jordan. There, the environment and landmine contamination is very similar to the one of Sri Lanka, where due to the decline in full scale war, I have not been able to go back after 2005. A tractor unit prototype has been developed in Italy and it is currently at the University of Genova, where it was preliminary tested. The machine is equipped with a pneumatic remote control unit, versatile enough to be fit on almost every kind of power tiller.

Technical drawings are reported in the project website (http://www.dimec.unige.it/PMAR/demining/), which has been constantly updated with simple explanations of all work stages, freely available to anyone who would like to build a new prototype of the machine, possible in any not specialized workshop, also in developing countries.

Acknowledgments

The number of people I would like to thank wouldn't fit in a traditional page; therefore you should read through these small lines. I'm sure your name it is here, somewhere.

This work has been long, challenging, enriching, incredibly interesting as it brought me around the world, totalizing, so much that now that it's coming to the end I start feeling a little bit lost, sometimes really difficult and sometimes really rewarding, but moreover it allowed me to meet a uncountable number of wonderful people, who not only accepted to give me some of their precious time and an insight of their long experience in their field, but who also showed so much enthusiasm into the project that some times they thanked me for having asked for their help. This has been unquestionably the greatest reward of my work. Therefore, it is "col cuore in mano" (my heart in my hands) that I would like to say thanks a million to: Prof. Ghigliazza, for accepting me as a student even if I came a bit in late in every sense, for his constant support and incredible trust. Andy Smith for being my godfather, as Serbam says, for having put me under his wings, encouraged, advised and supported me from Sri Lanka to Jordan. Chris Cellingsworth for his technical and material support. Prof. Snobar for welcoming me in Jordan as I was a member of his family. NPA people: Luke, Richard, Tom, Chamu, Pelle, for having hosted me in their wonderful corner of paradise and having taught me a lot about mine action; Heine, Stephen, Yasin, Damir and the dog team, Madaline and Serbam for making me feeling at home in Jordan. Eric whom it is fantastic to share so many crazy parties in crazy places with. Jochen for his help in tests and for the nice talks on the way to Risha. Mr. Samsam for his generosity. Yousef, Hassan, Ahmed, Rami and Redone, for making my work at RAMA workshop much easier. Christophe who is nice to meet time to time in strange places. Ross and Joan Macmillan for coming all the way from Australia for teaching me everything about agricultural tools. Andrea Pinza, Giampiero Giacomino, Danilo Coppe, Angelo Maragliano and Guglielmo Barabino and his workers for their invaluable support, Giuliano Gori for his invaluable support too and for his great phone calls. Enrico Alvigo for his consultations at the phone. People of Macchine Movimento Terra forum, for their suggestions and passion in answering my strange posts. Garage Montegrappa for having taught me the real mechanics. Prof. Bocco for supporting my application at the Institute Universitaire d'etudes du Developpement. Alberto, Lully e Mikka, Simone, Francesco, Matteo for having tried at least five times each to start the powertiller and made practical tests possible. Paolo, Ruzza, Szymon, Jawaad for having shared part of the work with me and for the nice trips we made together, virtually on the powertiller. Al Caruthers, Tim Lardner, Erik Tollefsen, Claudio Bruschini and Noel Mulliner for having offered their experienced consultations. Prof. Aiachini, for his suggestions on structural analyses. Prof. Balboni and Maurizio for their assistance in explosion pre-test. Vittorio, Roberto, Masa, WiKtor for their assistance during tests. Felix, Aazir, Aamir, Mauricio, Enrico, Fabio, Udayanga, Matteo of the PMARlab, for their constant nice presence around me and for having stood my moans. Gatto, Pietrocapo, Valsu, Mattetappo, Emma for the delicious karisma coffees and lunches. My always growing family who is always there, particularly Alce who is seldom closed and Rezia major, la mamma! Filip, Pietrocapo, Rudy and Sandra, Cabella people, for being a wonderful harbour where to go back everyday. Sorcha, Pisa, Lully, Fiffy, Giraffa, La Sagrada Familia, an old and incredibly strong institution. Simon for having appeared one day and for never stopping questioning. Gatto Masa, Danila e Gian for having believed strongly in Snailaid, I hope we can grow up together.

Table of contents

Glossary of acronyms

AP landmines, Anti Personnel landmines
AT landmines, Anti Tank landmines
CMAC, Cambodian Mine Action Center
DDG, Danish Demining Group
DTW, Development Technology Workshop
ERW, Explosive Remnants of War
EUDEM, the European Union in humanitarian DEMining
FSD, Fondation Suisse de Deminage
GICHD, Geneva International Centre for Humanitarian Demining
GPT, Ground Processing Tool
HD, Humanitarian Demining
ICT, Information and Communication Technologies
I.R.E., Istituto Ricerche Esplosivistiche
IUED, Institut Universitaire d'Etudes du Développement
LMAD, Linking Mine Action to Development
LTTE, Tamil Liberation Tigers of Eelam
MAG, Mine Advisory Group
MRE, Mine Risk Education
NABARD, National Bank for Agriculture and Rural Development
NCDR, National Committee for Demining and Rehabilitation
NGO, Non Governmental Organization
NPA, Norwegian People's Aid
P.T.O., Power Take Off
QFD, Quality Functional Deployment
SOP, Standard Operational Procedure
SWOT, strengths, weaknesses, opportunities, threats
TNT, trinitrotoluene
U-CD, User-Centered Design
UN, United Nations
UXO, Unexploded Ordnance

List of symbols used in equations

p	pressure
r	radius
R,b,h,d,a,y	distance, length
t	time
T, M	torque
w, δ	weight
W	work
Z	scale factor
ρ	density, volume of soil moved per time, rolling coefficient
u,v	velocity
g	gravity acceleration
γ	ratio of specific heat at constant pressure to specific heat at constant volume
m	mass
F, H, V,P,H,R	force
S	strength
I	moment of inertia
ω	angular velocity
A	surface, area
C	damping coefficient, dynamic load coefficient
E	energy
s	displacement
θ,φ	angle
μ	friction
ψ	tractive coefficient
σ	normal stress
ε	soil texture adimensional parameter
τ	tool width
z	tillage depth

Chapter 1 Introduction

(Deminers coming back from work, Mozambique, March 2004)

- Participatory design of technologies for development
- Powertillers for demining in Sri Lanka
- Agenda
- Thesis structure

1.1. Topic and problematic

With the exception of cases of items of Explosive Remnants of War (ERW) left over from the world wars in Europe, the problem of landmines and ERW occurs exclusively in developing countries.

It is there, where 85% [1.1] of conflicts that increasingly plagued our planet since the end of the Second World War have taken place and keep on proliferating.

As they are very cheap and easily available weapons, landmines have been and keep on being widely used. But, unlike other weapons, landmines, once buried, are not any more under control of the party and cannot be directed toward its enemy: very often it is civilians who actuate them by accidentally stepping on one years after that mine was put in place. This is the reason why, according to the principle of obligations towards civilians during conflict which has been present in international humanitarian law since the 1880’s, the use of anti-personnel landmines is banned by the majority of countries (all those who have signed the Ottawa treaty).

As research and development facilities in developing countries are usually scarce or non existent, technical solutions for landmine clearance come from Western countries, where research is either carried out in academic institutions or private companies selling demining equipment.

As a result, these kinds of technologies generally belong to one of two types: complex, high-tech types, whose justification and funding come from the need to produce high level state of the art research (i.e. European projects aimed to strengthen European excellence in world research) or simple to use but very expensive types, produced by commercial companies that sell in a very small market without enough competition. Sometimes, technologies are also developed locally, by Non Governmental Organizations (NGOs) who have good field facilities and technicians able to adapt existing technologies such as construction machines to the demining purpose.

In all cases, technologies for humanitarian demining are not designed together with local communities who might contribute consistently to the achievement of a good result with their first hand experience of the problem and gain useful skills that can be used later on for upgrading old technologies and starting their own innovation process that since the Stone age has proven to be a key factor of the human development process.

According to the Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti Personnel Mines and their destruction, also known as Ottawa Treaty, a **landmine** is a munition designed to be placed under, on or near the ground or other surface area and to be exploded by the presence, proximity or contact of a person or a vehicle.

Landmines are designed to incapacitate, injure or kill one or more persons. Depending on the target, being a person or a vehicle, landmines are defined as either Anti Personnel landmines (AP landmines) or Anti Tank landmines (AT landmines).

Humanitarian demining is the name commonly given to the process comprising several activities including **mine clearance** that leads to the release of mine affected land to local communities. Humanitarian demining includes technical survey, mapping, clearance, marking, post-clearance documentation, community mine action liaison and handover of the cleared land.

It has to be distinguished from military mine clearance, as the objective of humanitarian demining is to clear all of the mines and other explosive remnants of war from a given area to return safe land to the civilian population. For soldiers in battle, on the other hand, speed is essential, and they must accept greater risks. Therefore, military breaching may clear only a path through a minefield and may not destroy every single mine in the path of armed forces.

Humanitarian Demining, together with advocacy, stockpile destruction, victim assistance and mine risk education is one of the five pillars of the more comprehensive process which is called **mine action**, aimed at reducing the social, economic and environmental impact of mines and unexploded ordnance (UXO).

The Geneva International Centre for Humanitarian Demining (GICHD) has recently launched a new research project, seeking to better link mine action with development (LMAD). "It is seen as essential that mine action and development initiatives are effectively coordinated at all levels in order to align mine action with national and local development priorities, incorporate mine action within national development plans and budgets, increase stability of mine action funding and provide more effective mine action and development interventions" [1.2].

After conflicts, countries generally transit through three main phases: immediate post-conflict stabilization, reconstruction and then traditional development with assistance from international donors and financial institutions. Mine action activities take place along the whole process, targeting different aims in different phases, but it is generally the development phase which lasts for longer. In heavily mine affected countries, like Cambodia, mine action is still ongoing after sixteen years of official activities and more of informal village demining[1]. During the development phase, mine action is more likely to concentrate on community priorities because main roads and other infrastructure have already been cleared and re-opened.

Therefore, mine affected countries need to equip themselves adequately for the long haul and programmes have to assess their performance in terms of results that make a positive difference to people's lives.

In fact, although we know that millions of people living in 79 countries are affected by landmines [1.3], the size of the global landmine problem is not yet well defined, being missing indicators that measure the indirect impacts of landmines on people's lives. The post-conflict impact of landmines on development goes far beyond the direct and cruelest effects on human lives and

[1] Village demining is the name commonly given to mine clearance operations undertaken by villagers without formal training.

health; other important indirect effects are caused by the fact that landmines create obstacles to free movement within affected areas, posing restrictions on people's freedom and ability to access basic needs such as food, shelter, clean water, hygiene, transport, education and work, compromising their human development.

Nevertheless, the threat posed by landmines is only one among many others that people living in affected countries are facing everyday, such as the threats posed by HIV, malaria, road accidents, and so on. Therefore, approaching the landmine problem in relation to all the others, in the wider context of development, would lead to the possibility of being able to deal with it for longer and to do it in a more effective manner. In fact, donors' attention to demining is decreasing: donors are showing fatigue having spent money in demining activities for years without always having seen the results promised. The goal of having the world free of mines by 2010, is no longer realistic due to the slow and often incomplete nature of demining operations.

Approaching the landmine problem in the wider context of development suggests a change in the methodology for the design of humanitarian demining technologies.

That science and technology play a pivotal role in the development process is widely acknowledged. From pre-history, when the ages of mankind are named after the ability of their people to work different materials, to the industrial revolution that generated an exponential rate of growth of living standards, this has been so. Since 1820, 1/6 of the world's population has achieved high-income status and consistent economic growth and technology has been the main driving force behind this. “I believe that the single most important reason why prosperity spread, and why it continues to spread, is the transmission of technologies and the ideas behind them” [1.4], says Jeffrey Sachs, special advisor to the former UN secretary-general Kofi Annan.

In fact, one of the main differences between rich and poor countries is in their tendency to innovate; in poor countries inventors often do not have the incentive to invent because they know they will not be able to recoup the large fixed costs of developing new products. Even if the diffusion of technologies developed elsewhere can help development by bringing to poor countries new ideas and tools, often technologies are not designed taking poor countries' ecological conditions into account and therefore are not suitable to tropical or arid or mountain environments found in these countries.

Indeed, economic and human development would require that technical capacities suffuse the entire society, from the bottom up. In any developing countries, home-grown technologies would be needed to satisfy local needs in areas ranging from energy production and use, construction, natural hazards mitigation, disease control and agricultural production as well as humanitarian demining.

Therefore, a new methodology to design technology in a participatory way together with local end-users is here presented and used to design a new mechanical system for helping humanitarian demining operations in Sri Lanka.

Specifically, I propose to develop low-cost technology using local resources, adapting already available agricultural technology to demining tasks; leveraging mature technology would allow the exploitation of local knowledge already acquired through decades of use. Skills acquired in modifications of agricultural technologies to demining applications, could be used later on to increase agricultural production. Technological innovation in the field of agriculture is one of the major contributors to development.

This participatory approach would empower local communities by increasing their technical knowledge while making use of their own experience and skills.

1.2. Powertillers for Demining in Sri Lanka

Given that every mine problem is unique and strictly linked to the area where it occurs, the research focuses on one particular region: the northern area of Sri Lanka, the Vanni. This region is historically under control of the Tamil Liberation Tigers of Eelam (LTTE) and is where most of the fighting, between LTTE and government forces, takes place. Designing a technology for operation in a specific region helps to concentrate efforts on a well-defined problem; moreover, it allows local deminers to be involved in a project from which they will benefit and to exploit the knowledge they have acquired over long years working in the field.

I have chosen Sri Lanka for several reasons: people are generally well educated (having typically attended 10 years of school), enthusiastic, and willing to work and learn new skills. Additionally, at the time the project started, the country was facing an immediate post-conflict situation in which people were strongly involved in rebuilding the country. Unfortunately after presidential elections of November 2005, the situation deteriorated rapidly and the fragile cease-fire agreement signed in 2002 collapsed in everything but name due to almost daily violence. In January 2008, the cease fire was officially abandoned by the government, allowing a new wave of even greater violence to sweep the country. Although the ongoing conflict creates more difficulties in logistics and communications, I believe that a participatory approach to the design of a new technology could assume an important role in support of the efforts to achieve peace. New tools not involving face to face communication were devised and used for design phases prior to the effective prototypization.

At the beginning of the project, in January–February 2005, I spent one month in the Vanni region of Sri Lanka. The trip was aimed at establishing contacts, deepening knowledge of the local environment and improving communication skills to make the participatory contribution more effective. I interviewed groups of deminers to start the research in the right direction. I had the chance to better understand local needs and establish a reciprocal trust with local people as well as with expatriates coordinating humanitarian operations in the country. Most notably, in the field I gathered information by working on the functional requirements for a system of small, light and cheap demining machines to be used for working close to the deminers. The need of such a system arose from the study I conducted in 2004 in collaboration with the European support measure EUDEM2. At that time, when I asked deminers about their preferences for new machine technology, they expressed a strong desire for new machines that were small, light and cheap. They wanted them to help in the most boring/difficult parts of their job, particularly cutting vegetation and processing the ground, specially the hardest soils, currently scarified using a simple rake called heavy rake, to remove the soil hiding mines.

Based on these findings, I suggested adapting powertillers to demining applications. Powertillers are widely used and commercially available in Sri Lanka, and their second-hand market is widely spread. They are easy to transport as they are small and light, and they are available with different types of engines. The most powerful one (approximately 14 kW) is sturdy enough for my task, being Vanni region soil either sandy or soft because of alluvium type.

Power tillers, also known as walking tractors, two-wheel tractors or iron buffalos, have a great importance in their nations' agriculture production and rural economies. They are very versatile machines, having many attachments for performing different ground processing works, such as rotovators, moldboards, disc-plows, seeders, planters, and harvesters. Very important is also their ability to pull trailers with two plus ton cargoes.

The number of power tillers in developing countries is surprising high. China has the highest numbers that are estimated to approach 10M, Thailand has nearly 3M, Bangladesh has over 300,000 Sri Lanka 120,000, India 100,000 Nepal 5,500. Parts of Africa have begun importing Chinese tractors and Nigeria may have close to 1,000 [1.5]. Numbers are likely to increase as the availability of draft animals is reducing.

Fig.1.1. Use of powertillers in Sri Lanka used: transporting people and goods and for processing paddy fields.

By adapting power tillers to demining application I intend to increase the number of these machines available to rural villages. After operations they can be re-converted to their original agricultural use and exploited for increasing agricultural production.

As suggested by the NABARD association [1.6], to achieve the desired average farm power availability of 2kW/ha, necessary to assure timeliness and quality in field operations in India, agro

services centers could be established. There, machinery could be provided as and when it is needed on custom hire basis to the small and medium farmers who cannot afford to purchase their own machinery. In the same manner, in parallel to agricultural machines, the agro service centers could also provide machines for demining applications, based on agricultural machines. They could develop the modifications required to effectively address the demining problem locally, then hire these machines and provide assistance.

Therefore the aim of the thesis is twofold: first is to develop a new iterative, participatory design methodology integrating contribution of end-users nearer to the field problem and of researchers based in Western countries, where more tools (computational capacity) and resources (students and funding) are available, as well as any other stakeholder who wish to share its experience and knowledge. The new design methodology is aimed at producing a better, simpler and more cost-efficient product, making use of the knowledge of end-users who have being dealing on a daily basis with the problem the technology is addressing, and produced locally with available materials and parts. This methodology can be used to develop any kind of technology in developing countries. It is aimed at empowering local communities by transferring not technology but the concepts behind it, and pushing the innovative process that can lead them to their own development, according to their needs.

The second aim of the thesis is the use of such design methodology in a specific case study: the design and development of a new machine for humanitarian demining operations in Sri Lanka. The contextualization of the project allows the design to be really participatory and helps to develop a simpler and more effective solution, even if not universal. It is commonly recognized that a solution pretending to address the general demining problem, referred to as “Silver bullet”, is not feasible due to the extreme variety of scenarios, differing either for environmental and landmine contamination characteristics. Nevertheless, a solution thought for a specific area of a specific country can be employed in other regions presenting similar characteristics. This is the case of the southern minefields between Jordan and Israel, where sand and small plastic landmines are prevalent as they are in the Vanni. It is here, where I tested the ground processing tool of the machine, as it was nearly impossible at that time to introduce material in the Vanni due to the closure of the border.

The Study of Global Operational Needs, carried out by the GICHD in 2002, classifies humanitarian demining scenarios in twelve types.

Humanitarian demining scenarios

	Mountain	Hillside	Grassland	Woodland	Urban	Village
Soil	*Hard* Use of prodder difficult	*Medium* Pressure required; reduces safety	*Medium* Pressure required; reduces safety	*Soft* Use of prodder easy	*Hard* Use of prodder difficult	*Medium* Pressure required; reduces safety
Mineral contamination	*Low* Metal detectors can be used with minimal interference	*Low* Metal detectors can be used with minimal interference	*Low* Metal detectors can be used with minimal interference	*Low* Metal detectors can be used with minimal interference	*Medium* Metal detectors can be used but with some interference	*Medium* Metal detectors can be used but with some interference
Scrap contamination	*Nil* No scrap contamination	*Low* Some contamination, detectors still useable	*Low* Some contamination, detectors still useable	*Low* Some contamination, detectors still useable	*Medium* Not possible to use detectors given the threat	*High* Interferes and slows even prodding

	Routes	Infrastructure	Desert	Paddy fields	S-a savannah	Bush
Soil	*Hard* Use of prodder difficult	*Hard* Use of prodder difficult	*Soft* Use of prodder easy	*Soft* Use of prodder easy	*Hard* Use of prodder difficult	*Hard* Use of prodder difficult
Mineral contamination	*Medium* Metal detectors can be used but with some interference	*High* Impossible to use metal detectors	*Nil* No mineral contamination	*Nil* No mineral contamination	*Low* Metal detectors can be used with minimal interference	*Low* Metal detectors can be used with minimal interference
Scrap contamination	*Low*	*Medium*	*Nil*	*Low*	*Low*	*Low*

Fig.1.2. Demining scenarios, Annex G "Mine Action Equipment: Study of Global Operational Needs", GICHD, June 2002.

Demining scenarios by region

	Mountain	Hillside	Grassland	Woodland	Urban	Village	Routes	Infrastructure (primary routes)	Desert	Paddy field	Semi-arid savannah	Bush
South Eastern Europe	○	●●●	●●●	●●	●●	●●●	●	●	○	○	○	○
South-East Asia	●	●	●●●	●●●	●	●●	●	●	○	●●●	○	●●●
Southern Africa	●	●	●●●	●●●	●	●●	●●	●●	●●	○	●●	●
Horn of Africa	●	●	●●	●	●	●	●	●	●	○	●●●	●
The Americas	●	●●	●●	●●●	●	●	●	●	○	○	○	●
Middle East	●●	●	●	○	●	●●	●	●	●●●	○	●●	●
Global summary	●	●●	●●●	●●	●	●●	●	●	●	●	●●	●

This table shows the "spread" of demining scenarios found in each region. Each scenario describes a typical setting and group of criteria (terrain, climate, soil characteristics and hazards) which may exist together at a demining site. A detailed description of the scenarios is given in Annex G.

Key:
●●● Dominant scenario(s) in specified region.
●● Scenario frequently found in specified region.
● Scenario occasionally found in specified region.
○ Scenario not found in specified region.

Fig.1.3. Demining scenarios by region, Annex H "Mine Action Equipment: Study of Global Operational Needs", GICHD, June 2002.

From the table of fig.1.2, it can be seen that Soft ground, the type present in the Vanni region of Sri Lanka, is generally found in three demining scenarios: woodland, desert and paddy fields. Annex H of the same document (fig.1.3) reports the “spread” of demining scenarios found in each region.

It can be seen that woodland, desert and paddy fields scenarios are the dominant scenarios in many regions throughout the world.

The work of the thesis encompassed mechanical engineering work, which led to the realization of the working physical prototype of a humanitarian demining machine, developed according to the paradigm of *simple effectiveness,* targeting easy manufacturing, maintenance, disassembly and upgrading, that allowed to keep the prototypization cost lower than 10.000€, half of the maximum allowed cost.

The work also involved the studying of subjects not traditionally linked to engineering. The design methodology has been developed after researching the effects that landmines have on development and that technology has on society. This aspect, even if of lower importance to the technical committee and less relevant to a PhD in Mechanical Engineering, is very important to me and, in my opinion, deserves more attention by scientific academic institutions because understanding the context in which technology works is key to delivering more useful technologies, especially when dealing with technologies for developing countries.

1.3. Agenda and organization of work

Before starting the actual work on the mechanical design of the machine, I spent time setting up the framework of the thesis. After returning from Sri Lanka, where I spent one month working in the field under the kind supervision of Norwegian People’s Aid who became partner of the project and the mine action consultant Andy Smith, who later accepted to be my co-supervisor, I worked on the design methodology before translating end-users requirements into the definition of a possible task for me to achieve in the three years of PhD.

I also applied for a Diplome de Recherche at the Institute Universitaire des Etudes du Development (IUED) in Geneva, to formalize my willingness to learn more in the field of development studies and to approach the problem under a more interdisciplinary point of view. Unfortunately my application was refused, as I was missing the basic requirement of having already studied development subjects, and I was obliged to review my ambitious plans, leaving the studying of these subjects to my spare time. During my holidays I was able to visit mine affected counties and try to understand the impact of landmines in different scenarios.

A timetable of the work done is presented in fig.1.4.

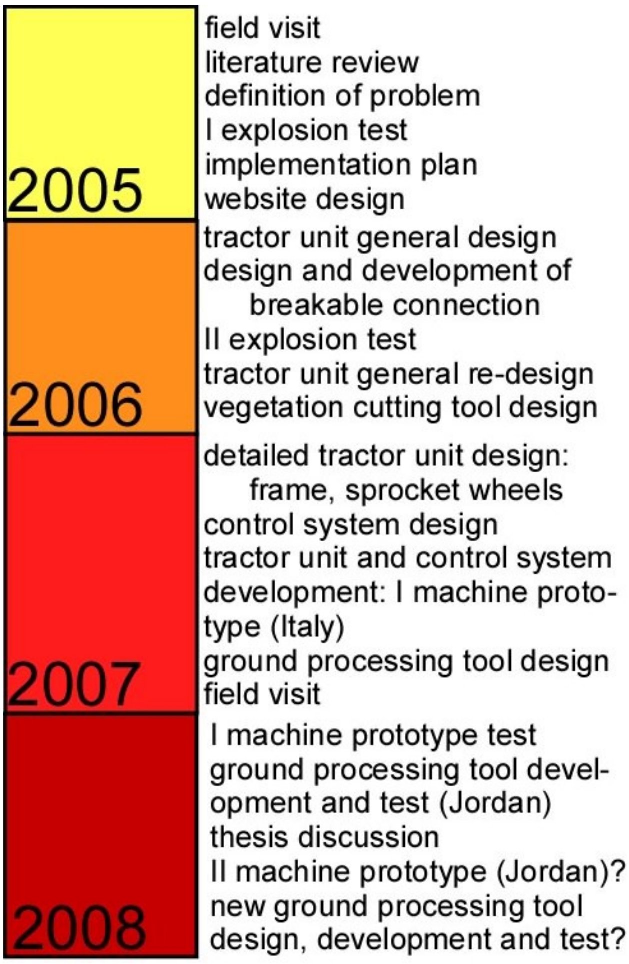

Fig.1.4. Work agenda

The final test has been done in Jordan where environmental conditions and landmine types are similar to the Vanni in Sri Lanka. The persistent conflict that obliged me to stay away from Sri Lanka during the whole design process, increased during 2007, achieving the worst tones after the withdrawal from the cease fire in January 2008 and preventing me from going back for the whole project time. As a result of this, test and development of the tool for removing landmines from the ground, the Ground Processing Tool, was conducted in Jordan, under the kind supervision of Norwegian People's Aid Jordan, the National Committee for Demining and Reconstruction (NCDR) Jordan and with the collaboration of the University of Jordan. During my last visit, the possibility of further collaboration with these entities was envisioned in order to complete the project with further iterations of the machine design.

1.4. Thesis structure

The thesis is composed by nine chapters plus references and appendixes.

The next, chapter 2 is dedicated to the literature review. After a brief introduction on humanitarian demining, including key definitions and concepts, I analysed the “non traditional” market of technologies for mine clearance, with particular attention on technologies derived from the agricultural field and technologies developed with a different approach, either produced in developing countries, such as Tempest and Arjun, or designed to be self-sustainable such as the Modular De-Mining Program. The chapter ends with the review of participatory approaches already in use in the field of humanitarian demining, after analyzing participatory approaches to research and development in use in other fields, from proper participatory rural appraisal used in agricultural projects to the more commercial and market driven user centre design. Appropriate technologies and collaborative software concepts are also touched.

The third chapter is dedicated to the design methodology and participatory tools used during the work. The relationship between technologies and particularly technology designed in a participatory way and human development is first investigated before presenting the participatory design methodology I outlined and used for developing the machine, the snail system. Proper participatory tools used during face to face sessions and collaborative tools used through the website when other type of communication was not possible, are then described.

The fourth chapter describes the work preliminary to the actual technical design, including first group interviews held with deminers in Sri Lanka, the analysis of the environment and existing local resources and the following definition of project task: the participatory development of a modular system for assisting humanitarian demining operations in Sri Lanka and in details the design and development of a tractor unit, based on a powertiller, and a ground processing tool, able to process the soil and make demining operations with the excavation tools currently used by deminers faster. Preliminary analyses on the suitability of the powertiller to be core component of the tractor unit and the development of different models for supporting later design decision making is also treated, together with the results of the first explosion test on the powertiller, before the presentation of the final design of the implementation plan.

The following chapters are more of the interest for the technical readers, as they treat the mechanical design of the tractor unit and the ground processing tool, their development and first preliminary tests. Unfortunately, time didn’t allow me to iterate the design cycles twice to achieve a better result by correcting mistakes found during the first preliminary tests. I hope I will have time to do it in the future; if this will be the case, I will update all news on the website.

The fifth and the sixth chapters regard the tractor unit. There are two chapters as the process to achieve the final design and prototype was long. Following the idea of designing a tractor unit that was a remotely controlled platform as versatile as possible, I first investigated the possibility to make it capable of withstanding landmine explosions under wheels, therefore able to support any kind of tool, from vegetation cutting tools, to ground processing tools also at the back. After looking into the physics of explosions and possible blast protections I designed, developed and tested a breakable connection devised to isolate the powertiller from shock waves by letting the wheel to drop off. A second explosion test showed that although the total energy transported by the wave was reduced, low frequency waves dangerous for the system were not blocked. Therefore, a second iteration of the tractor unit design was needed and the complete design of the final version with four sprocket wheels, tracks, frame embedding track tensioning system, additional external brakes mounted on the driven stub axles to allow remote control through skid steering is reported in chapter 6.

Then the ground processing tool, its design through all stages, and its final development in Jordan in Rama agricultural machinery workshop, and its preliminary test in the desert at the border between Jordan and Israel, with the support of NPA Jordan and the University of Jordan, is described in details.

Chapter 8 treats the control only briefly, as it was implemented together with three students attending the international master in robotics held at my department in 2007. In the context of their final project, they worked at the actual implementation of the control, by choosing components, designing the electrical and pneumatic system and developing the PLC controller software. Together we worked on the definition of system requirements and we made the preliminary choices on which type of brake to employ and what features to actuate by remote control panel, before making necessary calculations to dimension the system. Together again we did the assembly on the powertiller not yet modified to be tractor unit before their final presentation and we could assess that the system under no load worked properly.

Conclusions and future work is a very important chapter as a lot of work can still be done. The machine is not ready to be fielded, even if with only little work I believe it could be. The work to do is not too much, as both the tractor unit, the ground processing tool and the remote control system have been prototyped and need only to be integrated. As always happens time is not enough and by now I had to stop here, hoping to have the chance to complete the work soon.

1.4.1. Different colors for different readers

Even if I know that this thesis will be read only by few people, if any except from me, I use some rows to explain how it can be better appreciated by different types of readers. You might notice that some pages of this thesis are colored. Considering that people who might be interested into the work could come from three different worlds, the technical academy, the mine action field and possible the world of technology designers, I used different colours to highlight different types of topics (fig.1.5). Although people from the technical academy might be interested in all, they could skip the sections coloured in red, specifically targeting relationship between technology and

human development, participatory approaches and the design methodology, hopefully of more interest for designers. While these red pages expire within the first part of the thesis for coming back only in the appendix, the technical content expands till the end. Technical parts might interest also people from the field, who due to the lack of time for reading reports might be more interested in practical results than in theory and formulas: for them I have coloured in green pages including pictures, practical data and technical drawings. Pages coloured in grey are detailed description of explosion tests. Test results are analysed outside grey pages.

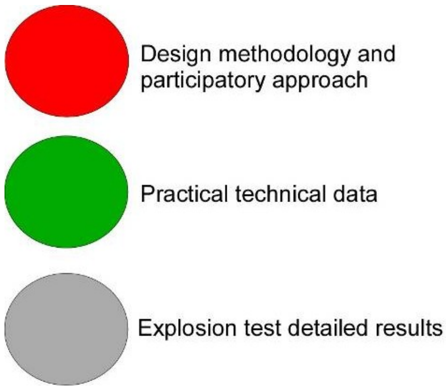

Fig.1.5. Different colors for different readers.

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Chapter 2 Literature review

- Humanitarian Demining
- Market of technologies for HD
- Agricultural technologies in mine action
- DTW and other similar projects
- Participatory technology
- Participatory approaches to HD

2.1. Humanitarian Demining: a short introduction

2.1.1. Landmines

Landmines are basic explosive devices that are designed to explode when triggered by pressure or a tripwire. Landmines are typically found on or just below the surface of the ground, where typically they are placed by hand, or, in some cases, by mechanical minelayers that can plow the earth and drop and bury mines at specific intervals.

Mines are often laid in groups, called mine fields, and are designed to prevent the enemy from passing through a certain area. The objectives achieved are mainly two: providing early warning of an encroachment by causing immediate fatalities or disabling injuries to the people who approach the mined land and denying access to the resources that the affected land could offer.

While more than 350 varieties of mines exist, they can be broken into two categories:

- **anti-personnel (AP) mines**, designed to detonate by the presence, contact or proximity of a person
- **anti-tank (AT) (or Anti-Vehicle) mines**, designed to detonate when a vehicle drives on them

Anti-tank mines are typically larger and contain much more explosive material than anti-personnel mines. Additionally, more pressure is usually required for an anti-tank mine to detonate (fig.2.1). Most of these mines are found on roads, bridges and large open areas where tanks may travel.

	Dimensions (diameter)	Expolsive charge	Activation force
AT landmines	300-350mm	5-10 kg	>100kg
AP landmines	70-150 mm	30-500 g	3-20kg

Fig.2.1. Typical differences between AT and AP landmines.

The basic function of both types of landmines is the same. A firing pin is connected to a mechanism which is actuated by a person either stepping on it, tilting the fuse, or pulling the tripwire. When the firing pin enters the detonator, it starts the explosive train by detonating. The shock wave, caused by the detonation reaction, then initiates the main explosive charge, sometimes via an interim “booster” charge, and the full explosion occurs (fig.2.2).

Explosion is an exothermic, self-propagating and very fast reaction. Therefore, it generates heat, its expansion stops only when the reaction substances are exhausted and it propagates at very high speed ranging from 2000 to 9000m/s. Explosion products are gases at very high temperature and pressure (for trinitrotoluene (TNT), T = 4000°C, p = 180.000atm) that when expanding create an intense pressure phenomenon that compresses the atmosphere around, making adjacent air molecules move that in turn make other air molecules adjacent to them move. This is known as the blast (or detonation) front (or wave); it contains approximately 50% of the energy originally contained in the explosive [2.1].

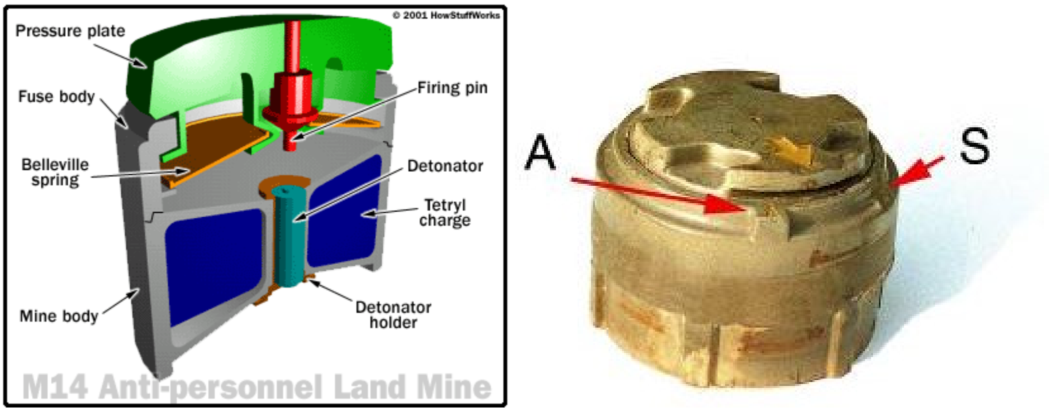

Fig. 2.2. Cutaway of a typical antipersonnel landmine and picture of the same (M14). (Sources: Howstuffworks; Andy Smith)

According to the way Anti-Personnel landmines are designed to explode, two types can be distinguished: blast and fragmentation mines.

- **fragmentation mines**; which are typically above ground or partly exposed in the ground. When they explode, metal fragments are propelled out at high velocity to a radius of 30 or even 100 meters. Some are able to penetrate several millimeters of steel at distances of up to ten metres. They may be detonated by tilt- or pin-pull fuzes, often attached to one or more tripwire.
- **blast mines**, which are typically buried in the ground close to the ground surface. They are designed to detonate when a person steps on them. As they are not metal cased, the injuries suffered are caused primarily by blast. Depending on the size of the mine, the bone in the foot may be broken, shattered or even powdered, and sometimes the entire lower leg will be broken away.

In addition to landmines, many affected countries also have unexploded submunitions (from cluster bombs) lying in or on the ground.

A **cluster bomb** is an air-delivered munition that ejects a number of small submunitions often referred to as bomblets. Up to 2000 bomblets can be dropped at the same time from a single cluster bomb, over an area of 0.23 km^2, the equivalent of more than two football fields. Unlike landmines, cluster bombs are designed to explode when they impact the ground, not to be victim initiated. In fact, cluster bombs affect the mine clearance operations only when they don't work properly and they fail to detonate. As they lie on or near to the ground surface, they can be initiated very easily, sometimes just touching them. When this occurs, they effectively act as fragmentation landmines because they are metal cased.

Although the maximum official failure rate of cluster bombs is fifteen percent, real numbers are much higher. During the Israeli-Lebanon war in August 2006, for example, the Mine Action Centre for Southern Lebanon estimated a failure rate raging between 30 and the 40 percent [2.2].

Given that each cluster bomb may contain hundreds of bomblets and they are fired in volleys, even a small failure rate can leave behind hundreds or thousands of submunitions scattered randomly across the strike area. The number of bomblets that could be found in Lebanon may be as many as one million. This kind of unexploded ordnance effectively adds to the number of landmines laying through out the world.

The extent of the global landmine problem is not known and is difficult to quantify with confidence. Although we know that 79 countries are contaminated by landmines [2.3], it is not possible to know the number of people affected directly and indirectly by the presence or the presumed presence of mines in their land. In fact, even if a high percentage of land after clearance turns out to be completely free of mines, all presumed contaminated areas have to be cleared or otherwise processed to ensure they are free of risk. Even where there are no landmines in the ground, the fear of their possible presence affects local communities' freedom of movement through, and the exploitation of, their land.

The devastating toll on human lives and health is unquestionably the cruelest impact of mines and unexploded ordnance (UXO). Although the number of casualties is very high, the toll on human lives is mainly due to indirect effects resulting from displacement of population, deprivation of earning capacity and poverty. Still, information on the human loss is to a large degree deficient, as most data collection on mine victims suffers from lack of reliability and coordination. Not only the number of mine victims is uncertain, but also the extent of the mined areas that the accidents refer to.

Of recorded direct victims, in 2006, as in previous years, civilians accounted for three-quarters. Deminers carrying out clearance activities remained the smallest casualty group with just over one percent of casualties, the same level as 2005, despite increased clearance efforts in 2006 and more varied tasks began, as with the Explosive Remnants of War (ERW) contamination in Lebanon. Most casualties appear to occur in rural areas while people are carrying out their daily livelihood and economic activities; this is especially the case in Laos, Vietnam and Yemen. This clearly demonstrates the negative impact of mines and ERW on the livelihoods of people, as fertile land, pasture, village environs and trade routes remain contaminated and dangerous [2.4].

On the 18th of October 1997 a "Convention on the Prohibition of Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction", known as Ottawa Treaty, was opened to signature; up to now, the number of State Parties, having signed the treaty is 155. Although this is a good result, the major mine producers, such as USA, Russia, Pakistan and China have not signed the convention. Mines have continued to be used after 1997 and landmines are still being laid today.

A process aimed at banning cluster bombs has also started. In February 2007, 49 governments attended a meeting in Oslo in order to affirm their commitment to a new international ban on cluster weapons.

2.1.2. Humanitarian demining practices

Until 2001 the UN standard for an area declared cleared of mines was that there was at least 99.6 percent probability that all mines have been removed or destroyed.

From 2001, the UN standard has changed in "Land shall be accepted as "cleared" when demining organization has ensured the removal and/or destruction of ***all*** mine and Unexploded Object (UXO) hazards from the specified area to the specified depth" [2.5].

The issue is how thoroughly to check and verify that all mines and UXO have been removed or destroyed.

Unfortunately, in most of the cases, after mine clearance operations have finished, the area cleared cannot be considered totally free of mines as the accuracy of the operation of landmines removal cannot be stated. Although current demining methods cannot guarantee that the land is entirely free of mines after it has been cleared, they are still used; this implies that by now, a solution that reduces the risk to a reasonable level is accepted as the best available.

Current demining methods are based on **manual demining**. Depending on the different situations, machines and trained animals can be used in combination with manual demining.

Before demining can start, surveys are needed to produce detailed maps of minefields to be cleared. In most cases, the survey team verifies a one or two meter wide safe lane around each minefield in order to define the minefield itself. A minefield can be surrounded with unknown land or other minefields. Although size can vary considerably, typical minefields are 100-200m across and 0.1-10ha in area.

Fig. 2.3. Typical minefield map, Cambodia. The safe lane, between the houses and the minefield can be seen. Dots are mines that have been already found, green areas have been cleared by machines.

There is an extreme variety in humanitarian demining methods and in the combination of different tools they use. Each program, in each country, has its own Standard Operational Procedures (SOPs) describing in details the clearance method that should be used.

Manual demining is a procedure in which mines are manually detected and neutralized by a human deminer. This is the most versatile and trusted method and therefore is present in every demining program.

Manual deminers can be equipped with different tools according to the particular soil they are clearing and to the landmines that are known to be found in that area. Information on the contaminated areas, the types of landmines and on the clearance depth that has to be achieved is gathered from interviews with local people who know about the conflict and about accidents already occurred.

Generally, manual deminers are equipped with detecting tools, such as metal detectors and excavating tools such as trowel and rakes, and some other traditional gardening tools such as sickles and scissors for cutting vegetation (fig.2.4). They may also be equipped with a prodder.

Fig. 2.4. Deminers equipped with different tools: metal detector (ADP, Mozambique), trowel (FSD, Sri Lanka), and rake (MAG Sri Lanka).

Usually a team of 30 deminers is assigned to clear each minefield. Two-man clearance parties work together on clearing parallel lanes, 1m wide, across the minefield, with each lane about 25 m from the next (considered to be a safe distance). In many cases, deminers are deployed in one-man one-lane clearance parties.

Sometimes, manual deminers work together with trained **dogs**. So far, dogs are considered the best detectors of explosives. Their sensitivity to this kind of substance is very high, enabling them to detect mines with low metal content at depths that render them undetectable by metal detectors.

Dogs are trained to indicate the presence of explosive by sitting a short distance from the location where the scent was discovered. When any dog indicates, the location is marked by placing markers on the edges of the minefield. Another dog will usually be introduced and will cross the area up to the indicated location again. Manual deminers can now safely approach the location across the zone which has been searched by both dogs.

The false alarm rate can be low, and the total clearance cost using dogs is about one quarter (or less) that of manual demining using conventional methods (Approximately US$0.15 per sq meter with dogs, $0.65 per sq meter using manual demining [2.6]). This, however, does not allow for the costs involved in training and preparing the dog and its hander to work.

Demining **machines** are often adapted from military armored vehicles, with the same or reduced size. In an early stage, machines were designed to clear a navigable path through a contaminated field to make the access possible for the military forces.

Because machines work fast and are relatively safe for the operator who is protected in an armored crew or drives the machine from a safe distance by remote control, they have been used in different applications. Machines currently available off the shelf belong to four different categories depending on their end-effectors. There are: flails, tillers, mechanical excavators and mine rollers.

The most common type of mechanical system currently on the market is the flail. A rotating axle, shaft or drum with attached lengths of chain-link along its surface imparts violent impact to the ground when rotated at speed. The second largest family of machines is the tiller. The tiller working tool consists of a rotating drum fitted with overlapping rows of steel alloy teeth or bits. The teeth grind and chew up the ground as the tiller drum is lowered to a selected depth. Mines are either detonated or broken up as the steel bits impale them. Mechanical excavators, adapted from commercially available machines by adding some armoring, are used to move suspected soil to a separate area for later inspection. Mine rollers are mine-protected front-end loaders or tractors carrying a heavy roller in front. Rollers are intended to activate mines by exerting a big pressure on them. Several different attachments derived from agricultural tools are then available for commercial equipment such as mechanical excavators, front-end loaders and commercial tractors either armored or not.

Fig. 2.5. The two mostly used mechanical demining technologies: flail and tiller.

2.2. The market of humanitarian demining technologies

Although metal detectors currently in use are much more sensitive than ten years ago and more machines have been used in the field beside manual deminers, the lack of the actual introduction of any entirely new technologies in common demining practices is surprising. Even if research and development efforts into humanitarian demining technologies have produced machines and sensors that have proven to be successful in increasing demining operations speed and safety during field trials, they have not been integrated in common practices.

This suggests that the reason for humanitarian demining operations to keep on relying mainly on manual demining is not to be looked for in the lack of funds or in the lack of high level technology specifically designed for the purpose, rather in the approach with which such technology has been designed and proposed to end-users. There is evidence of a lack of understanding of end-users realities, requirements and desires by demining technology developers.

Speaking in terms of the humanitarian demining market, technology developers (sellers) have poorly investigated the world of technology users (buyers) and have not been able to propose them attractive solutions.

There is an urgent need to develop new and appropriate technology for humanitarian demining. In order to develop such appropriate technology, it is necessary to make correct assumptions. Before technology designing can start, the “user market” must be analysed and requirements and operational constraints must be stated. It is not useful to give pork to a starving Muslim man. A recent study [2.7], committed by the Government of Canada, defined the market for humanitarian demining equipment and technologies as a “non traditional market […] as those who demand of equipment and technology generally are not able to purchase it, the suppliers of the products have no marketplace in which to sell their goods, and the purchasers generally do not need or use the equipment themselves, but donate it to the demanders.”

This is represented in simplified form in the scheme in fig.2.6, which shows how the humanitarian demining technology market works.

These observations motivated the study “Providing demining technologies end-users need”, funded by the European support measure EUDEM2 and carried out by the University of Genova in the person of myself in 2004. The research showed that the current state of field use of off the shelf machines was limited, especially if compared with sensor technologies. The aim was to ascertain the current demining technologies available in various contaminated countries and end-users feedback about them; the audience targeted was both the researchers approaching the problem of designing new demining technologies and NGO workers in affected countries. During the three months spent in the field, I visited nine organizations working in four different countries: Mozambique, Namibia, Sri Lanka and Cambodia [2.8].

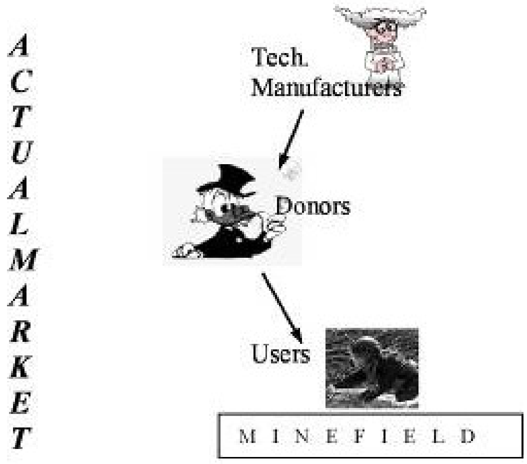

Fig.2.6. Humanitarian demining technology market.

While gathering various data, I asked nongovernmental organization logisticians about the maintenance costs of technologies in terms of the operating cost, salary of operators, downtime due to mechanical failures, time between failures and cost to repair failed machines. Generally, I found a huge difference between the maintenance costs of a machine and that of a sensor. Taking as an example data gathered in Mozambique, the maintenance costs per month of a machine in use at an organization were US$530 while the cost for maintaining a sensor was $194. These calculations do not even take into consideration the cost of training, which lasts for 25 days for a machine and less than one day for a sensor [2.9].

Thus, I believe high maintenance costs are one of the key factors behind the low adoption rate of machines by demining organizations. In my calculations, the high maintenance expenses were primarily due to the excessive cost to repair, multiplied by the high frequency of machine failures. I concluded that demining machines available on the market are complex systems that have not been conceived by the deminers who use them; nor have most machines been developed specifically for the environment in which they are being used. However, the organizations visited had few resources invested in personnel and workshops for mechanical technologies, each using between zero and two machines. An exception was represented by one organization, employing nine different mechanical technologies. All machines were adapted from mature technologies modified with locally available material in a specialized workshop.

During the summer of 2006 I visited another demining program in Abkhazia, Georgia, where many machines were in use, covering all operations. In this case as well, the presence of a specialized team of mechanics helped with the daily maintenance of machines.

By using the scheme in fig.2.7, it can be seen that the cost-efficiency of such locally developed machines is much higher than the ones that were developed elsewhere. This is due to the fact that machines developed locally have initial lower cost, shorter down time and lower repair costs. Among such mechanical technologies were machines built upon construction equipment, armored when necessary, using off-the shelf attachments such as vegetation cutters or sifters, trim cutters, locally produced rollers designed to mechanically activate mines when towed on suspected areas as well as rakes and ground scrapers.

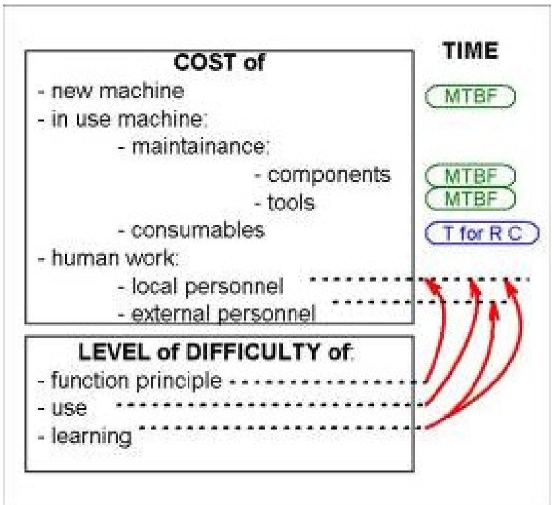

Fig.2.7. Cost-efficiency paradigm.

However, it is shown that investing in machines requires also investments in maintenance capabilities. In fact, a new philosophy has recently proven to be successful: some machines are currently delivered with a mobile workshop and the technicians in charge of taking care of the maintenance for the whole duration of work. While this approach can be very effective, it does not empower local communities as there is no knowledge transfer; therefore is more suitable for emergency responses than for the development phase.

Among mechanical technologies available on the market and documented in the Mechanical Demining Equipment Catalogue 2006, published by the GICHD, the cheapest is Tempest Mk V. It costs 120,000 USD and is classified as multi-tool system presenting a range of attachments from vegetation cutter to ground engaging head. It is largely produced in Cambodia in the Development Technology Workshop using local materials and facilities. Although not adapted from any existing technology, it is designed to incorporate materials that are locally purchased within developing mine affected countries such as Cambodia and to be easily repairable without factory support. Opinions about this machine vary, but DTW offers an upgrade package which extend the normal working life of Tempest, as all machines can be completely stripped down and disassembled before being refurbished with any new factory modifications or equipment used. The upgrade package costs 20% of the original purchase price.

Generally, the cost of machines increases as the size increases, mini and medium flail systems weighing from 3000 to 14500 kg costing between 220.000 and 300.000 USD, other than Tempest multi-tools weighing from 4700 to 7500 kg costing between 200.000 and 425.000 USD and Tillers weighing approximately 50.000 kg costing around 1.500.000 USD.

Unfortunately, the price of many machines presented in the Catalogue is not reported, making it difficult to analyze the difference between mechanical demining technologies adapted from mature technologies such as tractors or construction equipment and other technologies. Nevertheless, among advantages of machines adapted from other technologies is often mentioned the availability of spare parts from local dealers of the manufacturing company producing the prime mover.

2.3. Agricultural technologies for humanitarian demining

Between technologies available on the market and reported in the Catalogue of Mechanical Demining Equipment, I have analyzed with more attention the ones derived from the agricultural sector. Even if their price is relatively high as they are still sold on the small humanitarian demining market, it is very useful to see in which application different agricultural tools are used to address mine clearance. Except for the Pearson minefield tractor, all other prime movers are not coming from the agricultural sector being either specially designed remotely controlled units or commercial excavators and front-loaders. The Pearson tractor (fig.2.8) represents an exception also because of the idea that drove its conception: minefields often occupy productive land which can be exploited even if contaminated by landmines if an opportunely armored tractor is available. Therefore, the first Pearson tractor, called Pearson Survivable Demining Tractor (fig. 2.8), was a 10 tonne 4x4 tractor, armored and equipped with open cage wheels, designed to resist detonation of anti-personnel landmines. As the last version, which instead is based on a John Deere medium sized 6920 tractor with 110kW powerful engine, the Pearson Survivable Demining Tractor can support any kind of agricultural implement, attachable at the front or at the rear to the three point linkage attachments which are standard for every type of tractor. At the same time, it supports also specialized tools, designed by Pearson engineering company appositely for humanitarian demining, some more traditional such as the mine roller or the magnet and others more similar to agricultural tools commonly used for different applications, such as the sifter, the comb, the heavy soil loosener and the lighter spring tine cultivator.

 

Fig.2.8. Pearson Survivable Demining Tractor (Source: Mechanical Demining Equipment Catalogue 2003) and Pearson Minefield tractor (Source: Mechanical Demining Equipment Catalogue 2006).

The Pearson sifter (fig. 2.9) is designed to be pulled by the tractor or other suitable prime mover of minimum 50kW power with mechanical and hydraulic power take off. It is based on a commercial agricultural de-stoner. It cuts the soil at the selected depth with a set of horizontal shares; these lift the soil on to a slatted vibrating conveyor. The soil falls through the slats leaving mines, stones and large clods deposited in a windrow behind or to one side of the sifter for manual removal. Before using it, ground must be prepared by removing vegetation and rolling to break up clods.

Similar kinds of sifters are produced also by other manufacturers of humanitarian demining equipment such as Armtrac Sifter and the KZ Sifter produced by the Iraqi company Khabat Zangana Company (KZC) (fig. 2.9). Hendrik Ehlers Consult (HEC) in Naimbia produces a slightly different sifter called the HEC Rotar Mk-I sifter system (fig. 2.9), which is a front-mounted sifter drum used to scoop a bucket load of soil and process it. Processing happens when the sifter drum is rotated: particles smaller than 40mm x 40mm are caused to fall from the drum through a round steel bar mesh. Material remained in the drum is visually checked for the presence of anti personnel landmines by deminers.

All sifters are designed for anti personnel landmines. The Pearson Mine Comb (fig. 2.10), instead, is an anti-tank mine clearing tool. It is mounted in front of the prime mover and operates by combing large objects including mines gently to the ground surface from which they can be disposed of in an appropriate manner. The mine comb is very similar to the Mine Plough (fig. 2.10), another tool designed by the same company, Pearson engineering. The mine plough is addressing military demining and it is pushed by a tank. A raking action brings mines to the surface and moves them to each side of the vehicle. Another tool using the same principle of raking the ground and lifting up landmines in front of a prime mover called the Mine Clearing Cultivator has been developed by the U.S. Army CECOM Night Vision. Also different models of fork shaped tools exist, both for anti personnel and for anti tank landmines. Generally they are attached to excavators.

Fig.2.9. From the top left: Pearson Sifter, Armtrac Sifter, KZ Sifter and HEC Rotar (Source: Mechanical Demining Equipment Catalogue 2006).

Fig.2.10. From left to right: Pearson Mine Comb (Source: Mechanical Demining Equipment Catalogue 2006); Pearson Mine plough attached and in details (Source: http://www.pearson-eng.com).

Record of the research and development of a machine for humanitarian demining employing a sifter system similar to the ones presented above is found in the paper "The MiSa 1, an agricultural machine with demining capabilities", written by Detlef Schulz and published in the Journal of Mine Action [2.10]. Unfortunately no other reference or picture is available. The core of the machine is the vibrating sifter which performs an almost automatic mechanical separation of soil and metal parts, through the use of a metal detector and few other sensors. The sifter is mounted on a tracked chassis which is operated by radio remote control. It was specifically designed for clearing military areas in Germany contaminated with ammunition, but taking in consideration also requirements typical of Bosnia, Cambodia and Africa.

2.4. Development Technology Workshop and other similar projects

The Development Technology Workshop (DTW) produces the cheapest machine on the humanitarian demining technology market. It is a small no-profit company undertaking product design and technology for developing countries, operating in Cambodia, I had the opportunity to visit in 2004. It is affiliated to the Development Technology Unit of the University of Warwick in United Kingdom, a research centre specialized in technologies for developing countries rural development. The philosophy adopted by DTW is different from the ones driving other companies producing demining equipment as viability [2.11], sustainability and suitability to local production are fundamental characteristics of the technology they produce. They attempt to develop technology that can promote development and is suitable for developing countries. Recently they started working into new projects regarding the production of low-cost technologies for blind people, such as mobility canes and Braille writing machines, water and sanitation as well as energy production.

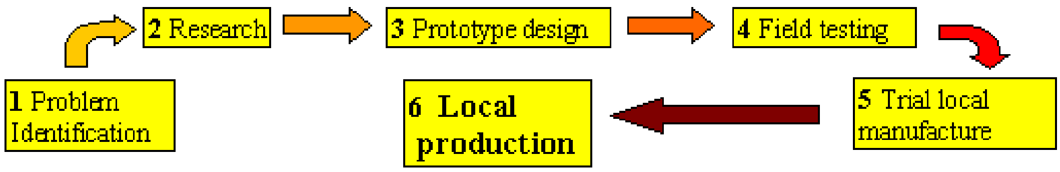

Fig.2.11. DTW products stages (Source: http://www.eng.warwick.ac.uk/DTU/mines/index.html).

The DTW's stated mission is to improve the livelihoods of poorer people through job creation and by introducing locally manufactured equipment into the small industries sector. DTW products go through the six stages represented in fig. 2.11. The major advantages of this approach are the realization of cheaper equipment and the creation of long-term, sustainable indigenous capacity specialized in the production of demining equipment.

At the moment there is one Development Technology Workshop in Cambodia. There, work 33 Cambodians, of which half with disabilities, together with 3 expatriate engineer/technicians. Local (Cambodian) end-users are involved into the development of new technologies in two ways: at the first important stage of the design process, the needs assessment, and during production as they are hired for the actual manufacturing of the technology. This process was not developed when work on Tempest began, with its first design being conducted in UK. Although designed for the Cambodian environment, the Tempest machine has been donated to Bosnia and Africa. This proves two important facts: the common assumption that locally made low-cost technology produced in developing countries is of low quality is wrong and the idea of involving end-users into the design process works.

The project presented in this thesis aims at expanding the approach used by DTW by involving local end-users into the whole design process of new technologies. I ensured the integration of end-users' contribution to the first needs assessment stage and tried to involve them in proper design choices, after having explained the main concepts behind them. This is easier when dealing with mature technology that most of the people already know and possibly use, such as powertillers.

Moreover, I included other stakeholder contribution into the design, such as the one of technicians working in workshops, blacksmiths, professors teaching agricultural subjects, people experienced in earth moving machines and everybody else who believed he could contribute. The final result is a technology end-users will own both physically and intellectually. In fact, I designed a machine which is much simpler and lower cost (see appendix IV) that what is available now, even of Tempest, and can be built in any unspecialized workshop that can be found (or easily built) in developing countries. The participatory approach I used led to the development of a technology whose technical drawings are freely available in the internet and can be built everywhere. It is not intended to be commercialized.

Another project that was worth to investigate because looking into the relationship between landmine clearance and other development initiatives is the Modular De-Mining project undertaken by De-mining Systems UK Ltd, represented by Roy Dixon. It is not at an advanced stage as DTW, being mainly a proposal waiting to be funded, but it has some interesting ideas behind it. The project aims at developing self-sustainable technology [2.12] for humanitarian demining. The assumption behind is that with the current method of foreign government donation the demining industry can only expand relevant to the amount of funding that is available to it. Considering the problem relatively to other development problems such as HIV or other pressing needs, funding for the demining industry seems to be peaking out and starting to decrease in size. Therefore, De-mining Systems suggests applying engineering business principles to humanitarian demining by proposing a new technology that generates its own funds. The modular demining machines would simultaneously clear vegetation and landmines cultivate the ground and plant crops. After harvesting, these crops could be sold on the open market and money used to pay back for the demining, giving a return to the original investors. Although, in my opinion, the sustainability of the modular de-mining machines proposed is compromised by the high complex and high tech modules attached to the tractor used as prime mover, the model proposed for self-sustain demining activities is very interesting as it is intended to help reducing the dependency of local communities on outsider donors.

At last, another project I analyzed is the infield development of Arjun machine by the Indian NGO SARVATRA in collaboration with NPA Sri Lanka and Andy Vian Smith, in Sri Lanka. This is interesting because the overall cost of each machine is approximately US$30,000, less than a good four wheel drive vehicle.

For more than a year, SARVATRA has been using adapted construction-site machines to provide the platform for vegetation cutters. The platforms are low-cost earth-moving machines with hydraulic arms designed to carry excavation buckets for use on building sites. The hydraulic arm reaches out into the minefield while the machine stays on safe ground.

With NPA assistance, those platforms have been armored and new ground preparation tools have been made. The platforms are being used in advance of the manual deminers. The tools remove dense undergrowth and scarify the ground, raking it to depths beyond that needed for confident mine clearance. The mechanized vegetation cutters and rakes are not designed to expose or detonate mines, but merely to break up the ground so that manual demining can be rapidly conducted behind the machine.

The use of widely used plant machinery means that spare parts are readily available, servicing is simple, operation is straightforward and the machine can be converted back to conventional uses by retrofitting its original tools in a matter of minutes. This versatility is unique and guarantees that the machines will not have to be scrapped when their demining roles are over.

Arjun is another good example of simple technology, built around commercially available mature technology, designed by end-users.

Fig.2.12. Tempest (Source: http://www.eng.warwick.ac.uk/DTU/mines/index.html), Modular de-mining machine (Source: Roy Dixon), Arjun machine (Source: Andy Smith).

2.5. Participatory technology

The concept of participatory design was born in the context of research and development in the field of agriculture. It arose as an answer to the Green Revolution, that in the 1960's and 1970's brought to a dramatic increase in world food production, despite a massive industrialized, monoculture agriculture implementation, made it possible by the transfer of new technologies, such as fertilizers and new types of more productive breeds, from Western countries to developing countries. This industrialized type of agriculture led to the loss of local traditional practices and biodiversities as well as to pollution and erosion of the soil, due to the introduction of chemical products, in a way that by many was seen as unsustainable [2.13].

Participatory research and development is an approach to learning and innovation, in which a wide range of actors, users and stakeholders are required to participate. It redefines the role of local people from being merely recipients and beneficiaries to actors who influence and provide key inputs to the process and at the same time enhance their knowledge [2.14]. In the agricultural field, the approach involves collaboration between researchers and farmers in the analysis of agricultural problems and testing of alternative farming practices. It makes use of participatory tools (fig. 2.12), which are very simple and creative communication tools, designed to help two-way communication by largely exploiting visual techniques, such as ranking and rating tools, where end-users are asked to rank and rate images representing possible choices. The final aim is to improve farmers' livelihoods by proposing sustainable solutions suitable to the local environment and exploiting local resources. At the end, solutions achieved by participatory research and development are intellectually owned by all participants who become less dependent from outsider help and are later on encouraged to start their own innovation process.

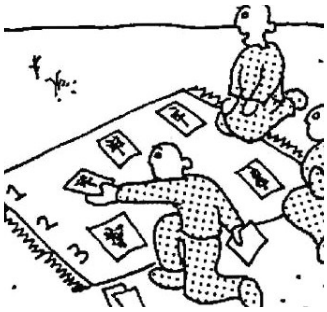

Fig. 2.13. Visual representation of Ranking tool (source: The Community's Toolbox (1990). http://www.fao.org/docrep/x5307e/x5307e00.htm)

The change of the agricultural research and development approach into a participatory one reflects a more general change toward the idea of human centered development, formalized by the United Nations Development Programme (UNDP) in 1990. Beside the average income, new indicators have been introduced to measure the human development index. They aim at measuring human wellbeing, first of all by addressing the satisfaction of primary needs such as house, food and sanitation and then by targeting human freedom, in terms of capability to make choices. Implicitly, it is understood that development cannot be achieved if there is dependency from outsider help. This also leads to a conscious exploitation of local natural resources, promoted also by the raising awareness of the global warming problem.

Following the change toward a more human centered vision, at the same time, the concept of **appropriate technology** started forming. It was introduced by the economist E. F. Schumacher in the book Small is Beautiful, published in 1973. From the acknowledgment that our economy is not sustainable, he proposes a shift from technology transfer to the design of appropriate technology, which is defined as technology that is designed with special consideration to the environmental, ethical, cultural, social and economical aspects of the community it is intended for

[2.15]. With these goals in mind, appropriate technology typically requires fewer resources, is easier to maintain, and has a lower overall cost and less of an impact on the environment. A related term is also **intermediate technology**, used to define technology that costs more or are more sophisticated or complex than those currently in use in developing nations but still much less costly, or more accessible, than those tools that would be used in developed nations. According to a definition elaborated by the British architect J. Turner a truly appropriate technology is a technology that doesn't make users dependent on the system over which they have no control [2.15]. A very good example of what can be defined as appropriate technology is the 100 dollar laptop, developed within the One Laptop per Child project, carried out at Media Lab of Massachusetts Institute of Technology (MIT). The outcome is a very cheap laptop specifically designed for children in developing countries, robust, consuming low energy and rechargeable by human power.

Although addressing problems of sustainability and dependency from external donors, appropriate or intermediate technologies do not specifically involve a full participatory design process. End-users are involved at the initial stage in the definition of requirements but are not generally asked to give their contribution in following design choices. Instead, an increased participation in technical design can be found in the development of commercial products. Some companies use techniques known as Quality Functional Deployment (QFD) [2.16] or User Centered Design (U-CD) [2.17] to improve their products by better identifying and meeting customers' needs. These processes are aimed at producing more usable and easier to sell products but are not aimed at enhancing end-users knowledge of the technology or the concepts behind.

Another field, in which, participation finds space is the Information and Communication Technologies (ICT) field, where **collaborative software** is being implemented. It consists of software providing different users with the ability to create and manage information through synchronous or asynchronous communication using different channels, mainly supported by the Internet. It has been suggested that Metcalfe's law — the more people who use something, the more valuable it becomes — applies to such software [2.18]. Collaborative software represents a good tool to favor participatory design, by providing a means through knowledge of different users, not necessarily located in the same place, is shared and improved.

An example for all, of successful use of collaborative software is Wikipedia, the encyclopedia where definitions are inserted by the same users, which has more than 2 millions articles and it currently ranks among the top ten most-visited websites worldwide. Another interesting collaborative project carried out at Massachusetts Institute of Technology (MIT) Media Laboratory is ThinkCycle, a digital platform where end-users in developing countries meet with university students in Western countries and provide requirements to them for designing some useful technologies they need. The project was born from a student idea of creating an online database of well-posed problems and evolving design solutions [2.19]. In practice, the platform supports problem formulation and design exploration through the extensive use of forums, allowing ongoing dialogue among many distributed participants, plus files sharing. At the moment, there is no a suggested structured design cycle to follow and little use of visual communication, not allowing less educated end users to take part into the design.

Although differing in audience, all participatory design methodologies analyzed are iterative processes. Sometimes, as in the case of user centered design, low fidelity prototypes are used to give end-users a physical representation of that particular aspect of the final product that is under investigation, and allow them to make relative design choices.

As every process involving discussion and consensus building, participatory design activities take longer time than traditional ones; instead of the time to market, functionality, intellectual ownership and sustainability are key aspects of the final product. Building trust and developing community capacity takes time. Moreover, time is needed both at the planning stage and at the implementation stage of participatory sessions: use of fantasy is essential both to maintain a high level of attention and also to enhance people creativity by suggesting new ways of thinking.

2.6. Participation in other fields of mine action

Participatory tools are already used in mine action activities. Mostly, they are employed in Mine Risk Education (MRE), to enhance a two way communication between practitioners and listeners: active, dynamic and creative communication is considered very important to convey more efficiently a message and promote behavioral change [2.20]. **Mine risk education** is one of the five pillars of mine action, between, advocacy, stockpile destruction, victim assistance and demining. Apart from saving lives and limbs, mine risk education goals are to reduce the socio-economic impact of landmines and promote development. These are achieved through public education, communication and community liaison, intended as continued information sharing between mine affected communities and mine action actors, from deminers to international donors, to assure that end-users priorities are opportunely addressed and end-users are informed about activities undergoing in their land. It is community liaison the most interactive part of MRE, as educators and beneficiaries are both resources for reaching a more complete risk reduction [2.21]. An example of use of participatory tools in this phase is the identification with the local community of possible alternatives to common practices, made unfeasible due to the presence of landmines, such as the relocation of a new well if the original one is in unsafe area.

Recently, Norwegian People's Aid (NPA) has published a study on community participation in mine action [2.22]. Starting from the development in 1999 of Guidelines for Mine Action Programmes from a Development Point of View, known as **Bad Honnef guidelines**, addressing the need to move from a preoccupation with the landmines themselves to a focus on the people and societies affected by mine and UXO, the study analyses examples of existing mine action interventions involving local community participation in three different areas: mine risk education, impact assessment and clearance. While, mine risk education activities explicitly involve the delivery of a message to communities and therefore are naturally more prone to the use of a participatory type of communication, the use of participatory techniques for impact assessment and moreover clearance is less obvious and deserves more interest. A technique for impact assessment, I had the chance to see implemented in Sri Lanka when I was there in 2004 and 2005, finalized in the country after several tests and now used by NPA in almost every programme, is **task impact assessment**. It consists of three phases. Phase one foresees the use of interviews based on two semi-structured questionnaires, one aimed at a reliable community representative and the other to individuals directly affected by the landmine problem. Interviews are followed by a community meeting to cross check results obtained previously and ensure a true representation of the community. The output is a clearance plan outlining priorities in each mine affected community. Phase two is a brief and informal check-up during clearance, while phase three happens after land handover to evaluate the actual impacts and to compare them with the ones expected from phase one: results are then recorded in a report including charts and statistics. Community studies as a tool to determine the impact of mine action programmes are still in their infancy [2.23]. Traditionally, the sector has had a strong focus on technical performance: the mine problem was defined in terms of mines or total area of land suspected of being contaminated by mines. Only after the reorientation toward the definition of the problem in terms of the impact of mines on human populations, communities started to be involved into the assessment process.

Instead, the contribution of local communities to demining is as old as demining itself. In Afghanistan, where the first humanitarian demining operations began in 1980s, local people were trained as deminers, given basic tools and sent back to their villages to start clearing. The programme was considered as unsuccessful and the experience was not duplicated in future projects. Nevertheless, in some countries such as Cambodia, **informal demining** by villagers with no proper tools or training continued on an as-needed basis, covering the inability of the formal mine action sector to meet the needs and priorities of communities living in mine affected areas. Only recently, attempts to bring informal deminers up to the standards of professional teams through training started. In Cambodia, two similar projects started in 2004, under Mine Advisory Group (MAG) and the Cambodian Mine Action Centre (CMAC). They created demining teams by recruiting the poorest members of mine affected communities to work as deminers in their own communities under the formal supervision of the organization. Deminers are trained for several weeks by experienced staff of the organization and work following the organization

Standard Operational Procedures (SOPs). Usually they are hired for a short term and paid less than a traditional deminer, as they live at home, not in campsites as traditional deminers.

Incidents records are promising, being zero for MAG and a minor one for CMAC [2.22]; they suggest that the approach leading to an increase of involvement of local communities and a handover of responsibilities to them is a possible way forward.

In the case of the rake system in Sri Lanka, local communities participated also to the development of a new demining technology. Simple rakes, locally sourced, were used by both government and Tamil forces in demining operations, before Norwegian People’s Aid was brought into the country to advise the local demining agency. Rather than changing the approach, NPA refined the tool and introduced it into their SOPs. The rake system is one of the simplest and most efficient demining methods implemented worldwide. As all techniques born in the field at community level, it is well adapted only to the environment were it was designed or to similar ones; it is not a universal clearance method.

Chapter 3 Design methodology

(Logo of the non profit assotiation Snail Aid – Technology for Development, founded with friends during the PhD time)

- S&T and human development
- Participatory Agricultural technology (PAT) for HD
- The snail system
- PAT for HD website and participatory tools

3.1. Science and Technology and human development – space for participatory technology

Human development requires three broad areas of need and capability to be satisfied. First, adequate provisioning for basic human needs - food, shelter, clothing, health and other necessary services – through both public and private effort. Second, development of basic human capabilities; these are, in Sen[2]'s conception, the substantive freedoms a person needs to lead "the kind of life he or she enjoys". They include health, education, knowledge and skills. Third, space for people to apply their innate and acquired assets, individually and communally, to achieve higher welfare outcomes. The defining features of such space include an environment of stability (political, social and economic), of democracy, a human rights culture, and freedom for all to operate as political and economic agents [3.1].

Human development is a means towards an even higher ideal, human freedom. An especially important freedom is that of a choice. At certain levels of deprivation, people cannot exercise basic choices that are essential for a dignified human existence, choices that every human being should have as a matter of right. For instance, they do not have the choice to seek medical help when sick, to have clean water, to eat decent food or to send a child to school. Poverty robs people of such basic choices.

Poverty can be considered in itself an emergency and the very antithesis of development. It perpetuates itself by creating disease, conflict and hopelessness and its consequences are severe: its greatest cost is the expansive destruction of human potential it causes.

Low incomes constrain access to education and poor people in poor countries lack the basic capabilities that support innovation and the transfer, adaptation and diffusion of technology. And technology is strictly linked to development as it is a tool for, not just a reward of, growth and development. Technology is like education—it enables people to lift themselves out of poverty.

Although technology has recently assumed a negative tone as many mankind problems are traceable to technology, such as the incredible power of death and destruction of chemical weapons, or the landmine problem itself, and the extensive damage to environmental resources though pollution and unsustainable exploitation, overall progresses in science and technology do help human development.

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[2] **Amartya Kuma Sen is an Indian economist, philosopher who won in 1998 the Nobel Prize for Economics for his contribution to welfare economics, including his work on human development theory.**

To share this point of view it is useful to analyze the etymology of the word. The word **technology** comes from the fusion of two old Greek words: *τέχνη* (transliterated as techne), art or craft or every kind of knowledge that finds a practical application and λόγος (transliterated as logos), word. Therefore, literally technology means word or discourse about the way things are practically made. With time, the word technology assumed a slightly different meaning. In one respect, the term has come to mean something narrower, the above definition would admit art or politics as practical outcomes, nobody now would consider them to be examples or subsets of technology. In another respect, this definition is now too narrow, for when most of the people speak of technology today they do not only refer to the technological knowledge, but also to the technological process and to the technological objects.

At light of etymology, the close relationship between technology and human development becomes clear. Advances in science and technology in terms of progresses in knowledge on how to do practical things, have been driving the development of human beings from the Stone Age. The desire to innovate and find ways to do labor-intensive activities using less man power is innate in the mankind. The ability to do it, by dealing with problems and finding practical solutions, can be defined as technology, and also the outputs of the process, the practical solutions achieved, can be defined technologies. When developed by the same people who need it and is not driven by a consumerist market but on basis of real needs, technology is not only sustainable and suitable to the environment where it is designed to work but can also promote end-users human development. It does so incrementally, according to a circular path (fig. 3.1).

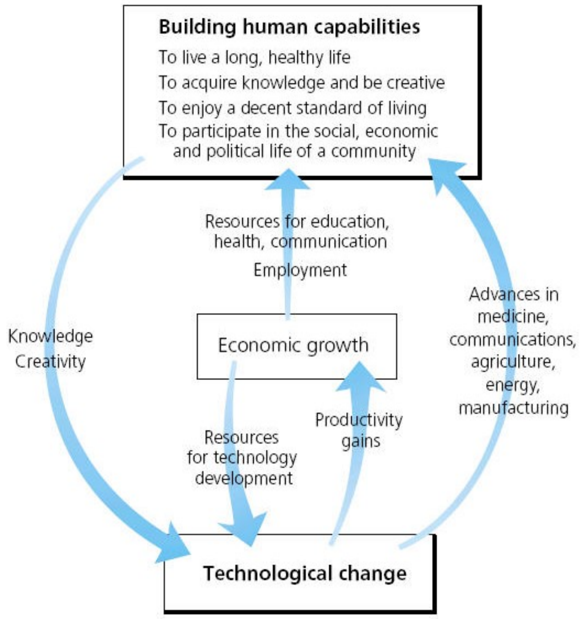


Fig.3.1.Links between technology and human development (source: Human Development Report, 2001, UNDP).

When the innovation process starts and a new technology is being produced, people participating to its development acquire knowledge and stimulate their creativity. Technology produced raises the efficiency with which they do things, possibly helping them to achieve a better income and extend their achievement possibilities over time. Time and resources, saved thanks to the increase in efficiency brought by the new technology, can be invested to meet higher wants such leisure or the desire to do research, experiment and discover more knowledge. People's ability to participate actively in the social and political life increases as well.

Unfortunately, the innovation process leading to the development of new technologies and the enhancement of human development, described by the circle in fig. 3.1, in many developing countries cannot start. Poor people, living in un-secure, conflict environments, are seldom innovators. They lack the basic resources they need to develop new technologies that could help them solving their own problems and start the innovation incremental process.

An external, possibly only one in time, input is needed to start the process. This could be in the form of a participatory design process, bringing together researcher of western countries and local people, through all stages of the technical design. A new methodology is required and is here proposed, representing a further step from the concept of appropriate technology, promoting participatory technology. It consists of a structured iterative design cycle in which end-users are involved at all choice-making stages; their knowledge is incorporated into the final product and at the same time they are empowered, by being proposed possible choices and explained some key concepts behind. The result of such a process is sustainable, appropriate, reproducible and upgradeable with no need of more external help.

Empowerment is an integral part of many poverty reduction programmes. It is seen as essential to promote human development and human freedom to help individuals and communities to function as agents for the improvement of their own wellbeing. Empowerment is not only about the state providing resources and opportunities, is about the citizens taking responsibility for self-improvement [3.1].

I argue that technology developed on the basis of real needs, in a participatory way together with people who expressed these needs, contributes significantly to their human development, by enhancing their knowledge and creativity and hopefully by solving a real problem and improving their lives. And such technology, because developed with end-users who live and know the environment in which it will operate, using local available materials and resources, is appropriate and sustainable. Not only, but it can be upgraded further, when and if it is needed, without anymore the help of outsiders. This technology and the knowledge behind are actually owned by the users.

"The world is not a zero-sum struggle in which one country's gain is another's loss, but is rather a positive-sum opportunity in which improving technologies and skills can raise living standards around the world" [3.2].

3.2. Participatory Design of Technologies for Humanitarian Demining

In the context of human development, it could assume particular importance the use of such a participatory methodology to design new technologies for humanitarian demining.

In post-conflict area, landmines affect human development in many ways. First of all they represent an obstacle to economic growth, because of the direct costs they inflict on governments due to fatal injures, the treating and rehabilitating landmines casualties and because of the opportunity costs of long term disabilities and lost productivity they cause. Moreover, until suspected areas are not treated for verifying the presence of landmines and, when they are found, mines are not removed from the ground, they impede the exploitation of resources these affected areas could offer. No matters if these areas are agricultural fields, roads, infrastructures or religious temples: if local people fear that they might contain mines, their choice to accede them is not a free choice any more. People can decide to avoid those areas or, if after balancing the weight of other risks they could face by not entering, such as starvation or some God punishment, they can also choose to enter or cross very well marked minefield, accepting the possibility to be injured. This happens often in places where mine affected areas cover a considerable proportion of land, such as in Cambodia. Here, people living near to the mined border with Thailand, deliberately decide to cross it illegally everyday, to go to work in the richer neighboring country, as they cannot afford to pay for the passport needed to enter through the official safe crossings. Therefore, landmines affect also human freedom, not last for the restrictions they pose on free movement among the country.

But relationships between landmines and human development can also be found considering other different natures of mines, i.e. as weapons or pollutants. As weapons, their availability and misuse heavily undermine affected communities vulnerability. The direct burden resulting from the threat of life, combined with the indirect burden of protection and avoidance, constitute a tax on the standard of living of a community. The indirect effects of weapons availability and misuse can include: a rise in the incidence and lethality of criminality; the collapse or erosion of social services; a decline in formal and informal economic activities (a potentially a rise of the illegal ones); the distortion of investments, savings, and revenue collection; and the dislocation of social cohesion and trust in communities [3.3].

As pollutants, landmines impoverish natural resources, the environment that naturally favors human development. Often landmines stay in the ground for years before they are removed and during this time cases can leak and release explosive in the soil. When mechanical means are used to process the ground, the top soil layer, the more productive one, is often completely removed, and when flails are used, landmine cases pieces can be scattered all around and left on the ground.

Adapting agricultural technologies to the humanitarian demining task can also help human development; skills acquired working at the powertiller-based machine can be used later on in other agricultural innovations.

Finally, the adaptation of technologies that are low cost and mature, by using resources available locally in developing countries, make the design methodology suitable to low funded technology development projects.

3.3. The Snail System

The Snail System (fig. 3.2) [3.4] is an iterative design methodology allowing a progressive involvement of end-users in the design process of new technologies. Snails are lines connecting subsequent steps of the design process that develop along a straight line indicating work progress.

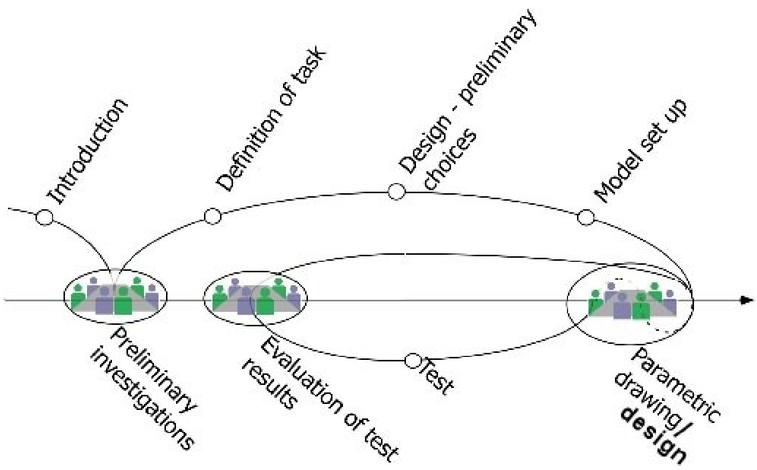


Fig.3.2. The Snail System.

Meetings with end-users happen along the straight work progress line. Every decision is made with end-users; only studies prior to these decisions, such as the preparation of possible choices, simulations and calculations, are carried out by researchers and later presented to end-users.

The design evolves along all the traditional steps, including the creation of models, as tools to support design decision making.

Models can be either mathematical, digital mock-ups, when prepared in university laboratories or very simple models made with material ready available, also called crap-ups [3.5], when done in the field together with end-users. The idea is making prototypes quickly, even very rough ones, to get the ideas flowing and to find out which direction seems most fruitful. Simple and partial tests are done with ready available materials and are evaluated by discussing together with people involved in the subject, at all different levels, from locals dealing with the problem everyday, to researchers living in western countries. Learning by mistake is very effective, especially at early stages of the design process.

Together with end-users, I have tried to involve many other possible contributors into the design process to make it more effective. People working for manufacturing companies of components I used, international demining experts, various representative of NGO's, people working in mechanical workshops, blacksmiths and researchers of various universities gave their precious contribution to the project.

Each Snail represents a work module necessary to carry out the main package of the total work for the project. The workflow of technology design is represented by Snail lines, as often it is iterative; the design process is repeated until a satisfactory result is reached. Each snail requires different work and preparation before meeting with end-users, but holding meetings with end-users for various snails at the same time can be done to reduce travel expenses. Graphically, two snails can overlap.

Also the methodology, the Snail System, is being designed through an iterative process; the scheme has been used, tested, evaluated and changed many times, during the technical design of different mechanical system modules. Different participatory tools and new techniques were devised at each iteration resulting in a new a improved design methodology. Once the technical design of the module under research in a given work package was satisfactory, the participatory methodology design was reviewed again for application in the next work package.

The changes into the methodology and particularly in the participatory tools used for involving end-users into the design were also justified by the impossibility for me to go back to Sri Lanka, after the intensification of civil conflict.

While, at the beginning of the project, I could use traditional participatory techniques, such as ranking and rating tools, later on, when no more face to face communication was possible, I used the project website (http://www.dimec.unige.it/PMAR/demining/) as communication channel, exploiting online collaborative softwares.

The workflow for achieving the final design, therefore, can be represented graphically on a line depicting the work progress as a family of snails, walking one behind the other, as shown in fig. 3.3. Each snail represents how the methodology evolves, together with the technical work leading to the design of a mechanical system module. Each snail is smaller than the previous one, needing less work and therefore shorter lines to be carried out. I believe that not only end-users but also researchers improve their efficiency and practical expertise and learn better skills along the process in both participation and technological design.

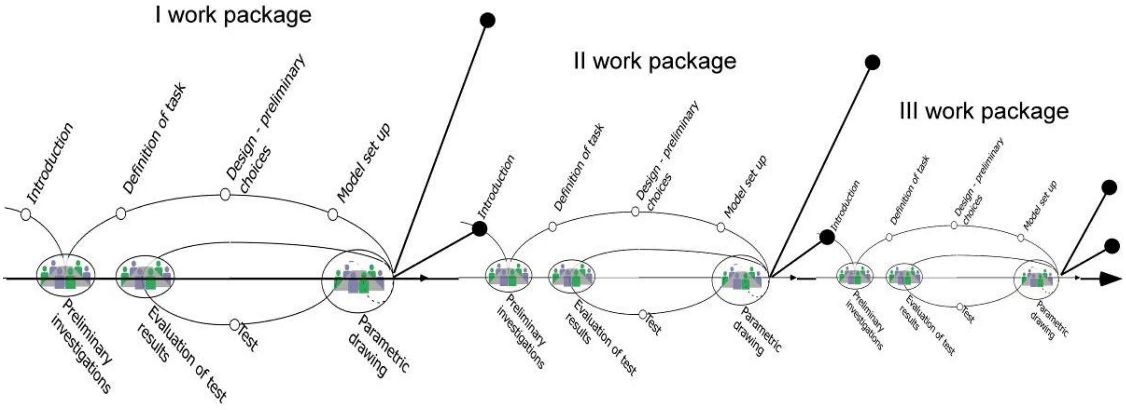


Fig.3.3. Family of Snails.

Of the two antennae for each snail, one goes into the next snail, indicating that the design methodology used in the next work package comes from the one evolved in the last work package, and the other antenna goes into the dissemination of ideas and experiences achieved in the previous work package.

3.4. PAT website and participatory tools used

At the end of the first PhD year, in December 2005, I have uploaded the first version of the website Participatory Agricultural Technology (PAT) for Humanitarian Demining online at the web address: http://www.dimec.unige.it/PMAR/demining. From that time on I have kept updating it every six months with work progresses. The website contains all the work done in the context of my PhD project; technical drawings, reports, videos and pictures are freely downloadable. The aim is first of all to inform the international community and all people interested about the progresses of the work, hoping to seek comments and advices on what should not be done, what could be done better and what is worth keep on doing. Then, is a tool through which I could thank all the people who contributed to the project, by offering precious suggestions or material, and moreover it offered a support for making the design participatory by using collaborative tools.

In fact, when it became impossible to involve end-users personally into the design process, I decided to use online collaborative tools through the PAT website. By using these tools it is possible to store documents such as presentations, excel sheets or word documents online and to view them either in the website where they are stored, or in any other website where they have been embedded. Different users can access the documents and modify them; all changes are appearing in real time in the website and can be seen by all visitors.

I have used power point type presentations, provided by Zoho services (http://www.zoho.com/) free collaborative online tools, capable to include text and simple drawings, to explain as easily as possible all design steps, and I have linked them to the main pages describing the work. Comments, errors or sketches could be added by any visitor, accessing the presentations by using the account created for contributors on Zoho. A page with instructions on how to add comments or modifications to them is appearing when clicking the rotating snails highlighting the interactive sections of the website. All presentations available on the website are reported in appendix I, while the thesis paragraphs describing the work presentations refer to have a small snail near the title.

Fig.3.4. Project website Logo and page with embedded the presentation for Tractor Unit / local resources.

Although the website has been visited by more than 1000 people from all over the world, unfortunately nobody has never modified presentations. They have been seen, but not changed. This might be due to the slightly time consuming procedure to add modifications or comments and probably moreover to the lack of active involvement of website visitors. A demonstration on how to use it, which was impossible for me to do in this case, in the future should be done in the field, to make end-users familiar to the system.

Anyhow, the website has proven to be effective in setting up collaboration and supporting participation of all stakeholders who contributed to the project: they could see pictures, drawings and download files and reports. It was used more as information tank, as feedback on the work was mainly received by emails. It also favoured real face to face participation. In fact, thanks to the kind donation I received from the Belgian company Exilis, after they saw it, I could develop the ground processing tool in Jordan, after adapting its original drawings to the material available in the local workshop, together with Yusef Abutimah, Hassan Omar and Ahmed Sabama, working in the workshop.

Statistics of the website suggest that it received attention from all over the world, but specially from countries where people who collaborated to the project work.

Fig.3.5. Project website statistics (April2008): number of visits and visitor location.

A portion of visitors of the website is constituted by members of the Macchine Movimento Terra (MMT, machines for soil movement) forum. Through the use of the online forum, people with first hand experience in agricultural equipment got very involved into the project, probably because of its humanitarian application and diversity from other problems traditionally posted. Not only they gave me precious suggestions but also sketches of their own ideas, such as the one of an electrical starting system for the powertiller engine.

Between more traditional participatory tools, I could use only in face to face sessions during the needs assessment phase, I employed interviews with groups of deminers using ranking tools and simple presentation slides clearly introducing the problem and trying to generate ideas (appendix I.I). As ranking tool, I prepared pictorial representations of different options and I asked the group of deminers interviewed to rank them according to different criteria such as level of difficulty for demining practices or level of confidence into human interface control system devices, such as buttons, levers, touch screen (fig.3.6).

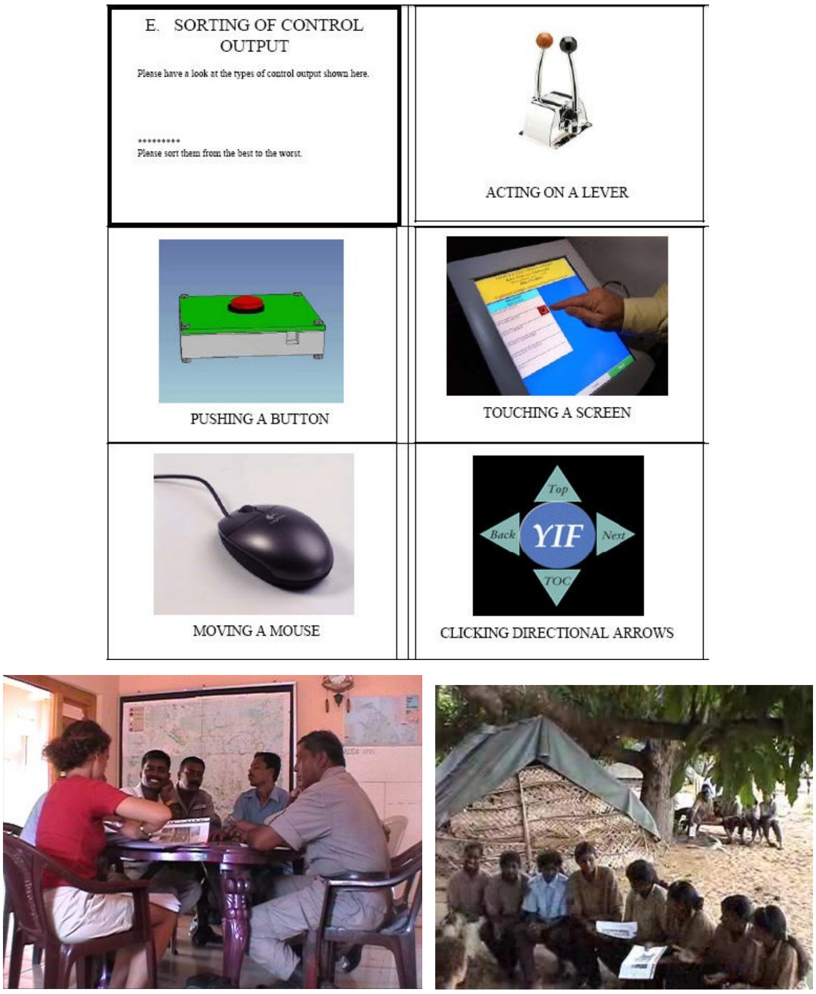


Fig.3.6. Ranking of human interface control system device and group interviews in Sri Lanka.

The most exciting participatory part anyway was the final development and test of the ground processing tool in Jordan, even if not structured. Participation took naturally place, after a short introduction of the project, the website and the participatory approach, as a consequence of the need to adapt my technical drawings to material already available in the workshop.

There, during the four days I have spent in the workshop working at the manufacturing of the tool, I could appreciate an increasing involvement of workers. The supporting frame devised to connect the tool to the three point linkage of the tractor used as prime mover in tests, was entirely designed locally. In the workshop I made calculations to verify the suitability in real time as ideas were coming out on how to employ an old frame to our application (fig.3.7).

I used participatory tools also while working with the students attending the international master in robotics for assigning final projects taking into considerations personal interests and knowledge; after having collected information about their skills using the scheme in fig.3.8, I use a matrix where each one of them could express his preference and his level of interest into every project proposed. The result, in the case of the team I supervised who worked with me at the control of the machine, was a very strong team of motivated people.

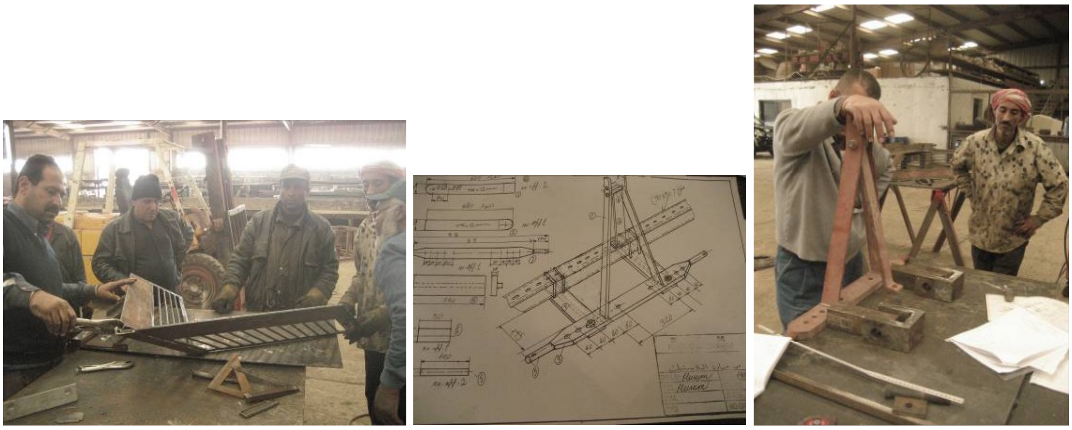


Fig.3.7. Two phases of the ground processing tool supporting frame in Jordan.

Fig.3.8. Skills, experience collection scheme and matrix for participatory choice of final projects (different colors correspond to different projects).

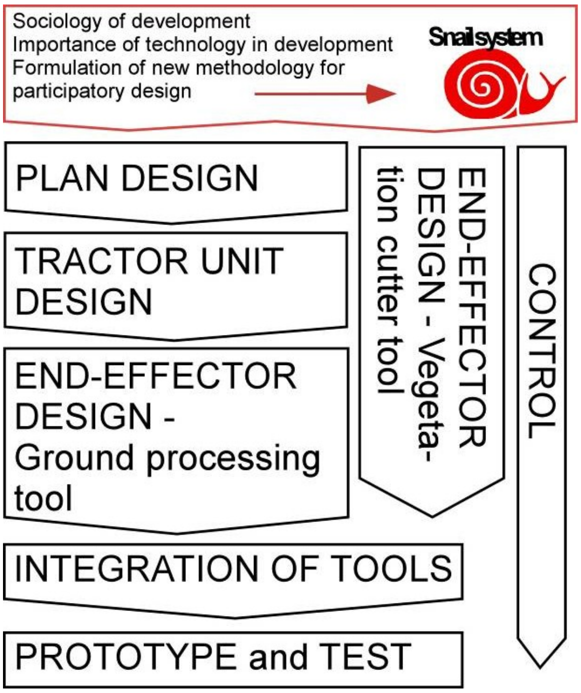
Apart from people involved in the project through proper participatory sessions, many other people contributed to the final design of the machine. Also a high school student, Fabio Rossi got involved into the project, he helped with the cardboard prototypization of the ground processing tool (fig.3.9) for a simple test aimed at assessing the effects of different design angles to the translocation of soil. The test was done in a sand test in the lab and details are reported in chapter 7. First he developed a Lego model of the powertiller and then used it as prime mover of cardboard models of the ground processing tool in the laboratory sand bed. On the last day we worked together he also came up with an idea of taking inspiration from the design of snowblades.

Fig.3.9. Fabio and his machine lego model and ground processing tool cardboard model.

The results presented in this thesis have been achieved only thanks to many different people with the most diverse backgrounds, from blacksmiths to researchers, from people working at repairing agricultural machinery to people working at the Geneva International Centre for Humanitarian Demining (GICHD), who made me available their long experience, accepted to spend with me some of their time and gave me precious suggestions.

Fig.3.10. Only few of the people who collaborate to the project.

Chapter 4 Implementation plan



- Understanding the environment in Sri Lanka
- Definition of task
- Design preliminary choices
- First explosion test
- Implementation plan

4.1. Needs assessment

The first work package of the PhD was the definition of the implementation plan. This could be done only after assessing what were the needs of deminers working in the Vanni region of Sri Lanka, what demining practices were currently in use and what technologies were already available in the field. I have conducted these preliminary investigations in Sri Lanka, during January and February 2005. Basing on the information I have collected in previous work, from group interviews with deminers of nine different NGO's around the world, about statements of needs "wish list" for new technologies, I worked on the functional requirements for small, light and cheap machines, to be used for working close to deminers [4.1].

I interviewed two groups of deminers working for NPA Sri Lanka, one of males and one of females. Both groups were composed by four section leaders. They were working in different areas; the minefield targeted by female deminers was characterized by heavy vegetation, mainly palm trees, and the minefield currently cleared by males was a grass covered, flat area (fig.4.1.).

Fig.4.1. Sri Lanka: minefield cleared by the women team interviewed for needs assessment, women interviewed and minefield cleared by men team.

Differences in current working areas, might have affected different answers. In fact, while the female team expressed desire for a machine helping them in cutting palm leafs (trunks don't need to be cut and are protected by the Sri Lankan law) men asked for a machine helping them processing hard ground, currently scarified using a simple rake, called heavy rake, to remove the soil hiding mines. After introducing the idea of my project, to design a new small machine helping deminers in the most boring/difficult parts of their job, I asked them to identify a possible task for the machine, to come up with some ideas, even if very stupid, and define some possible constraints. All answers are reported in Appendix I.I. and a summary is reported in fig. 4.2.

They generally expressed desire for small machines, preferably small enough to be fit at the back of the truck they use to go to work, able to process the ground in front of them, which could be used with other units in area reduction/verification process. Apart from the interest deminers showed into the project, I would like to highlight the creativity especially the men team expressed, supporting the finding from the EUDEM2 survey that there is unanimous opinion, held by organisation representatives, that deminers are willing to learn to use new technologies. In particular, I like the tiger-kangaroo idea of a mechanical arm like a tiger paw to be used as rake, moving soil toward a kangaroo-like pocket, where landmines are retained.

FROM GROUP INTERVIEWS:

- 2 teams visited (1 men, 1 women):
  4 section leaders + driver and medic interviewed in each team

- Main results:
  - They would appreciate having a small machine (no wider then the base stick) helping them while they work
  - Possible applications: raking ground instead of heavy rake and vegetation cutting, specially palm leafs cutting
  - Ideas:
    - Bio-inspired by tiger paws – kangaroo pocket
    - Dimensions similar to base stick, anyhow small enough to fit in the vehicle
  - Problems:
    - Roots of big trees
    - tripwires

NEED:

Small machine preparing ground in front of the deminer during demining operations, which could be used together with other units in area reduction – verification process.

Fig.4.2. Results from group interviews held in Sri Lanka, February 2005.

4.2. Environment and practices

4.2.1. Landmine contamination

Life in Sri Lanka has been marred by more then two decades of ethnic conflict, mainly between the national government and the Tamil militant groups led predominantly by Liberation Tigers of Tamil Eelam (LTTE) insurgency. Sri Lanka is a developing country, basing its economy mainly on the exportation of textiles and garments, and in smaller part on agriculture.

The struggle by the Tamil Tigers of the north and east for a largely independent homeland continues to cast a shadow over the economy. In late December 2004, a major tsunami took nearly 40,000 lives in Sri Lanka and caused massive destruction of property [4.2]. The number of International Displaced People (IDPs) is 186.893 [4.3].

After the civil conflict, still active, Sri Lanka is one of the worst mine affected countries in the world. The worst affected area, where most of the battles have been and keep on being held, is at the boarder between the area under control of the government and the area under LTTE control. The Vanni region (fig. 4.3), where the project is focusing is the LTTE controlled part. Sri Lanka has not acceded to the Mine Ban Treaty; the government has repeatedly indicated that its accession is dependent on the success of the peace process with the Liberation Tigers of Tamil Eelam (LTTE). Landmines are still used.

Fig.4.3. Sri Lanka. The Vanni region is pink colored (adapted from: www.reisenett.no/map_collection/sri_lanka.html).

In LTTE-controlled areas, mine action activities are coordinated by Tamil Rehabilitation Organization (TRO) and implemented by the Humanitarian Demining Unit (HDU). HDU activities are technically supported by four Non Governmental Organizations (NGO), Norwegian People's Aid (NPA), Mines Advisory Group (MAG), Danish Demining Group (DDG) and Fondation Suisse de Deminage (FSD). After the intensification of hostilities, only NPA continued to receive clearance from the authorities to operate in LTTE-controlled areas. In September 2006 the government impounded TRO's financial resources, forcing the HDU to halt demining operations [4.4]. Information on recent evolution in landmine contamination is still deficient and current practices reported below refer to operations that were undergoing in 2005 and 2006, when the cease fire agreement between the two fighting parties was still in place and humanitarian demining activities were ongoing. While new areas would be affected in new ways, maybe with new types of landmines or Improvised Explosive Devices (IED), adding complexity to the picture, the main landmine problem will stay the same.

One of the peculiarities of Sri Lankan contamination consists in the fact that mines are mostly found in patterns, along what are called “mine belts”. Mine belts have been laid by both LTTE and Sri Lankan Army (SLA), for defending purposes. Maps of minefields laid by SLA are available but they are lacking accuracy; reference points are missing, so that it is impossible to locate precisely where the map refers to, and in some places a not very accurate mine clearance already took place before official humanitarian demining started, making it impossible to compare the number of landmines recorded in maps with the number of landmines to clear.

Fig.4.3. Minefield under clearance by FSD in Napankulam, Vavunya, 19/4/2004. Map of minefield under clearance by FSD in Talaimannar West, Mannar, 20/4/2004 (crosses indicate where landmine were found).

The pictures in fig.4.3 show the typical mine pattern used in the Vanni: mines are laid in the ground in group of four, along defensive lines. (FSD uses yellow painted wooden poles to indicate places where mines have been found). Because of the typical mine placement, along belts, demining operations are mainly focusing on finding where the belt starts. Minefields are breached from a safe lane, previously cleared, along demining lanes 1,2m wide, at least 10m apart. When a mine is found, clearance goes on along a horizontal lane perpendicular to the breaching lane. Fig. 4.3. shows a typical clearance path. Blue-light colour indicates cleared lanes. Generally, the area between lanes is not cleared manually as it should be free of mines; their absence is verified by machines that, after clearance, are driven up and down the whole area.

4.2.2. Current manual demining practices

Unlike what happens in most demining programmes, no metal detectors are employed in the Vanni, as soil is ferrous and mines have very low metal content. Instead, ground is excavated at the depth of 100mm, specified by local authorities, to expose to eye sight buried landmines. Two simple rakes (fig. 4.4) with handler extended to 2m are used: light rakes to remove loose soil and hard rakes to process more compact and deep soil. The rake system, currently employed by NPA in Sri Lanka and Jordan, is also known as Rake Excavation and Detection System (REDS) (fig.4.4). It consists of full excavation, preferably achieved using only the light rake, which no matters how much force is applied on it, due to its numerous and flexible tines, the pressure it exerts on soil is lower than the minimum required to activate landmines (10464Pa, for Type72A, the most sensitive landmine found in the region). If soil is too hard and light rake becomes ineffective, the heavy rake is used to scarify ground; deminers place the rake head in front of them in the clearing lane and gently pull it back toward them.

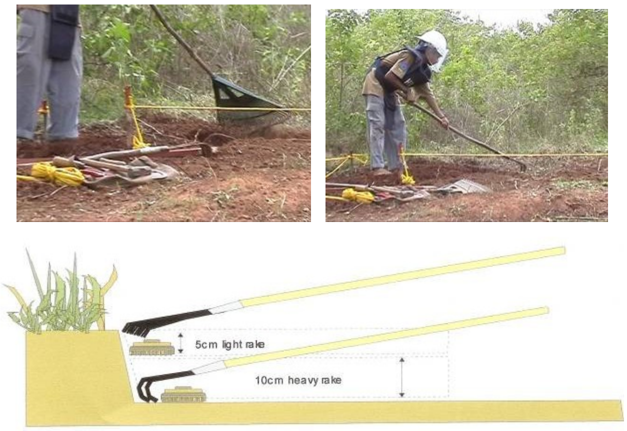


Fig. 4.4. Light and heavy rakes in use in Sri Lanka (pictures from the author, drawing from Andy Smith).

The two curved rake tines plough back through the soil; their curvature is such that mines are approached on the side and the pressure plate on top is not touched. The raking action is repeated for the entire width (1m) of the clearing lane. When a mine is discovered, it is exposed using either the rakes or other hand tools.

4.2.3. Soil and landmine types

Because it can be processed with simple rakes, soil of the Vanni can be classified as light or soft. It is generally flat to slightly undulated, as shown in the map in fig. 4.5, reporting the major soil groups present in the dry zone of Sri Lanka, where the Vanni region is.

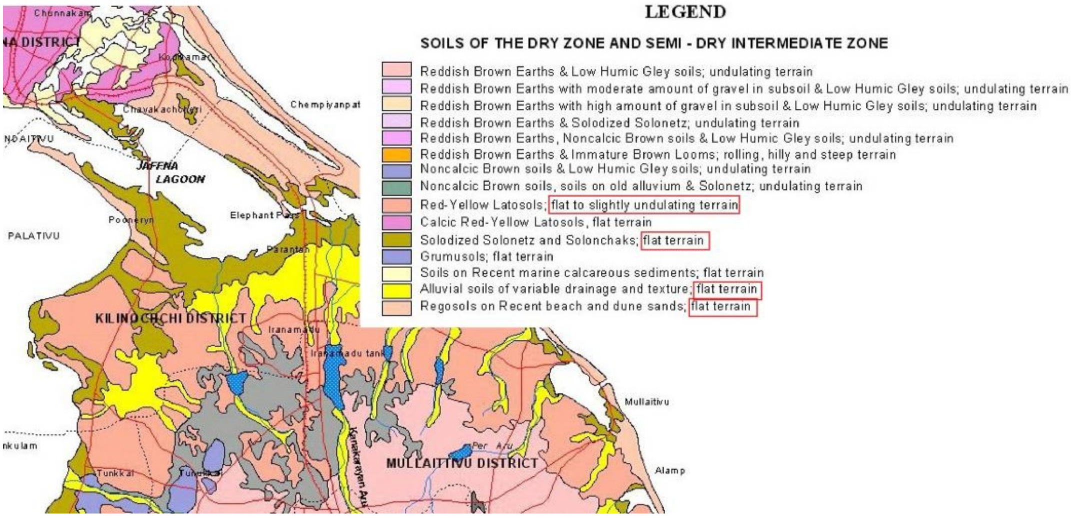


Fig. 4.5. Soil Groups in the Vanni region (adapted from: http://eusoils.jrc.it/ESDB_Archive/EuDASM/Asia/lists/clk.htm).

Metal contamination in disputed areas is sometimes very high, and especially in areas that provided “cover” for combatants.

Metal contamination in mined areas adjacent to areas of habitation can be extremely high when mined areas were habitually used as “rubbish” tips [4.6].

Different soils found in the Vanni are represented in fig. 4.6.

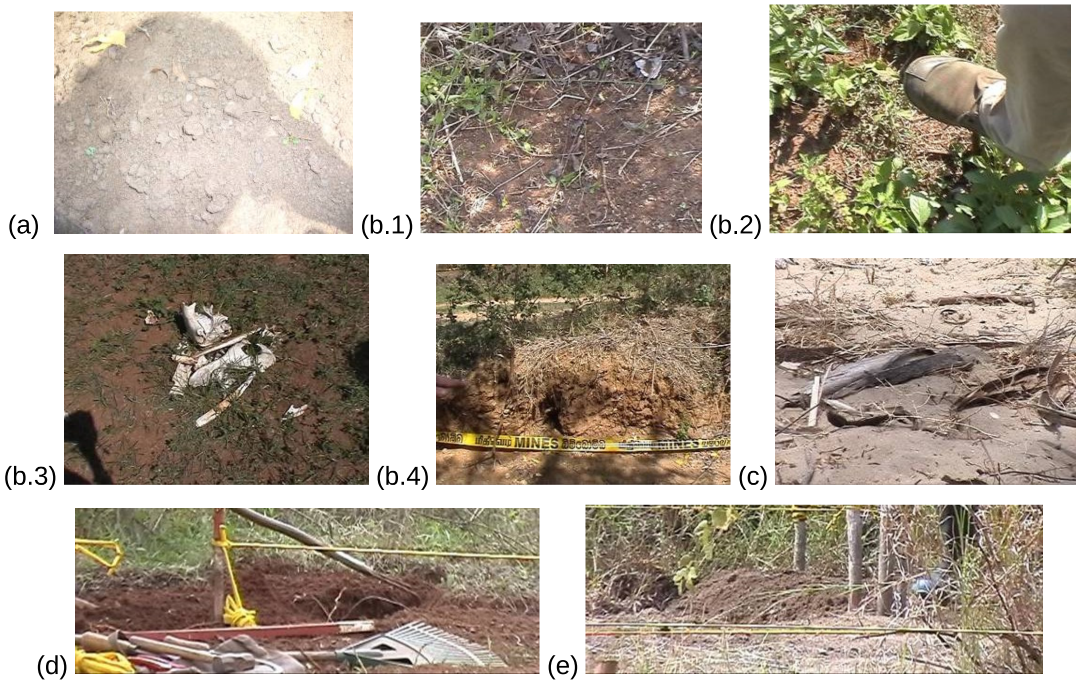


Fig. 4.6. (a) soil found in minefields: along A9 road from Vavunya to Kilinochi; (b) Napankulam, Vavunya, (b.3) particular of animal bones, probably dead due to a landmine explosion, (b.3) bump; (c) Talaimannar West, Mannar; (d) near to Kilinochi; (e) near to Elephant Pass

The soil parameters affecting ground processing and trafficability, I looked at were:

- strength, usually measured by value of cone Index, CI [kPa]
- cohesion, c [kPa]
- angle of internal friction, φ [°]

The typical value of cone index for Sri Lankan soil, I found in literature, is 500kPa. In fact, Somapala [4.7] states that cone index for alfisols soil, the most common type of soil, according to USDA soil taxonomy, the classification of soil types made by the United States Department of Agriculture, found in the dry zone, ranges between 360 and 400kPa within forest belt from 0 to 150mm depth and between 200 and 600kPa within cultivated soil from 90 to 150mm depth. While, Indraratna [4.8] states that in coastal soil layers after Tsunami occurrence, the cone index value is 500kPa in loose sand up to 500mm depth. Typical values for cohesion and angle of internal friction, general found in sandy soil according to an estimation by an expert, are cohesion between 7 and 15kPa and angle of internal friction of 30°.

Landmines mostly found (fig4.7) are small, antipersonnel, plastic, blast mines. Due to their small size and low explosive content, even if accidentally actuated by the action of the hard rake, they don't cause injuries to deminers wearing proper personal protection equipment.

Types of mines mostly found in the Vanni are P4-Mk1, Type 72 AP, VS-50 and some locally manufactured mines, the Rangan 'Jony' 99, a plastic cased mine based on the P4-Mk1, and the Jony 95, a blast mine wooden cased . Generally mines have been in place since 1994 and the pressure required to activate them is between 5 and 10kg, pinpointed on the fuse. Three of the common mines are classified as "minimum metal" mines and can be very hard to locate with a metal-detector.

The Johny-95,also called Rangan 95, was made in Sri Lanka by Tamil factions. The fact that it had a printed label and many have been found implies that at one time there was a production capacity. The mine is based on a block of wood 105 x 67mm with a 53mm diameter hole drilled in the base into which plastic explosive is pressed. In a hole on one side, a 9 volt battery is inserted. Due to the wooden case and the presence of the battery, this type of landmine decays very quickly and is unlikely to be still functioning after a long time it has been in place.

P4-Mk1
Height: 38mm
Diameter: 70mm
Explosive: Tetryl
Explosive weight: 30g
Operating pressure: 10kg

Type 72 AP
Height: 38mm
Diameter: 78mm
Explosive: TNT
Explosive charge: 50g
Operating pressure: 5kg

VS-50
Height: 45mm
Diameter: 90mm
Explosive: RDX
Explosive charge: 45g
Operating pressure: 10kg

Rangan 99
Height: 55mm
Diameter: 88mm
Explosive: TNT
Explosive charge: not known
Operating pressure: not known

Jony 95 (Rangan 95)
Dimensions: 100x60x60mm
Explosive: PE
Explosive charge: 150g
Operating pressure: not known
unlikely to work

Fig. 4.7. Anti Personnel (AP) Landmines mostly found in the Vanni.

Together with anti personnel blast type landmines, usually found under the soil surface, other explosive weapons can be found over the soil. These include Claymore type mines and improvised mines based on mortar bombs (fig.4.8). These are fragmentation types of mines, usually standing over the soil on legs and actuated by tripwire. UXOs are also present where battles occurred. The most common UXO in the Vanni are rifle and grenades (fig. 4.9), both of which are fragmentation devices. They are small but metal cased and they can threat people at a distance of 20m.

Two or three anti tank mines can also be found at the end of each mine belt.

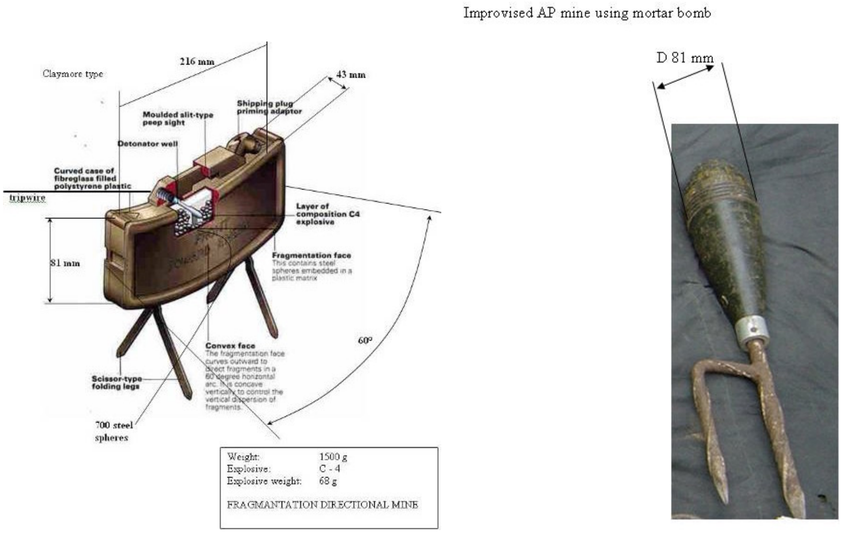


Fig. 4.8. Fragmentation devices found in the Vanni (Claymore and Improvised mine based on mortar bomb).

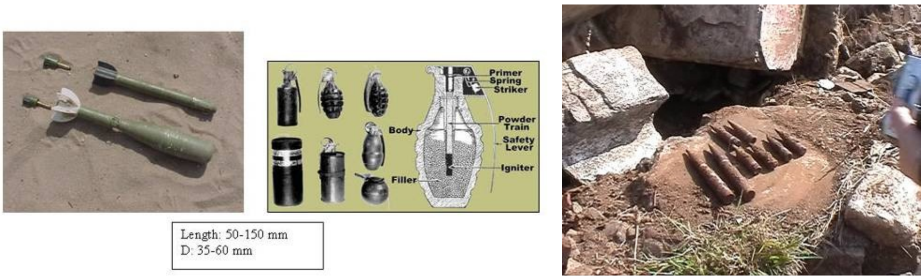


Fig. 4.9. UXOs found in the Vanni. The picture on the left shows UXO found near to a primary school in Vavunya.

Vegetation in the Vanni can be classified as belonging to three different categories. Low vegetation, where grass is prevalent, medium vegetation where bush is prevalent and high vegetation, when there is a high density of palm trees (fig. 4.10). Vegetation is cut using simple gardening tools like saw, sickle and shears.

Fig. 4.10. Examples of light, medium and high vegetation of the Vanni and gardening tools used by deminers to cut it.

4.3. Definition of task

Based on group interviews findings, and on the analyses of current practices and the environment, I suggested adapting agricultural machines to assist humanitarian demining applications in the Vanni region of Sri Lanka.

In fact, deminers asked for their preferences during group interviews, expressed a strong desire for new cheap and light machines, small enough to be fitted in the back of a small truck. They want machines to help in agricultural-like tasks: cutting vegetation and processing the ground, specially the hardest one, currently scarified using the heavy rake. In fact, no metal detectors are employed by NPA, the NGO partner of the project with the University of Peradeniya in Sri Lanka, as soil is ferrous and mines have very low metal content; instead, ground is excavated at the depth of 100mm, specified by local authorities, to expose to eye sight buried landmines. Two simple rakes with handler extended to 2m are used: light rakes to remove loose soil and hard rakes to process more compact and deep soil. Vegetation is manually cut with simple gardening tools like saw, sickle and shears.

Between small agricultural machines available in Sri Lanka I have chosen to employ power tillers, as they are very common and widely used, being one of the most important multi-purpose agriculture and transport vehicles in the country.

Therefore, the target of the project is to develop a **modular system using as core module a power tiller for assisting humanitarian demining operations** in Sri Lanka and equipping it with a **ground processing tool**, able to process the soil and make demining operations with the excavation tools currently used by local deminers faster.

The tractor unit module based on the powertiller, can be considered as a platform; it can support different specialised modules, targeting different tasks, such as vegetation cutting, or ground processing in different types of soil. In the three years time of my PhD, apart from the tractor unit and its control system, I had time to work only on the ground processing tool module, targeting the soil (soft) typically found in Sri Lanka. Anyhow, during this time, a module for vegetation cutting [4.9], especially palm leafs, has also been designed, but as it was topic of the final project of a master student, it is not included in this thesis. The whole report and technical drawings ready for manufacturing are available online at the project website: http://www.dimec.unige.it/PMAR/demining/machine_vegetationcuttertool.html.

To achieve the main goal of processing soil, as required by deminers, the ground processing tool has to substitute the heavy rake. Therefore, it has to process the soil at required constant depth and expose landmines by lifting them up on soil surface, possibly without actuating them.

Deminers will assist the machine: they will walk on its clear path using only the light rake to locate and remove landmines already lift up on soil surface by the ground processing tool. I have introduced manual mine removal in order to lower the complexity and cost of the machine, as well as to allow a quicker integration of it in operational procedures at the same time as addressing end-users needs.

In Sri Lanka, as in the rest of the world, deminers carrying out clearance activities are the smallest casualty group; although an increase in landmines and ERW casualties in 2006, with 64 victims, almost double than the previous year, there were no reports of deminer casualties during clearance operations in 2006 [4.10]. This shows that manual demining, the clearance technique mostly used, is not a dangerous activity. At least not, when procedures are followed, personal protective equipment is worn and proper tools are used. Where low-cost, simple technology can help most, is in assisting deminers in their work, by absolving them from most boring/repetitive or most physical demanding tasks.

As landmines have been laid in well defined patterns along mine belts, the most efficient way to employ the machine would be simply to locate the beginning of the mine-belt; when the first landmines are exposed, and the belt therefore located, deminers can proceed to manually clear the belt without wasting energies and time working where there are no mines, while the machine can be employed to locate the belt in the next mine field.

A slightly different ground processing tool could be designed to collect landmines at the same time as raking them out of the ground, to lower deminers work. Apart from being further from deminers needs, this solution is more suitable to environments where landmines are found at random locations. In fact, where a high concentration of mines is known to be, it is faster and cheaper to proceed with manual demining than with the machine that can be damaged by too many explosions.

Even if other bigger and more dangerous landmines can also be found, including fragmentation types and anti-tank mines, the machine is targeting only small plastic landmines, which are also the most common types, as a major requirement for it is to be low cost and therefore with limited power. Before starting clearance it is generally possible to say in which minefields bigger and more dangerous mines can be found: the machine will not be used in those areas.

Therefore, the machine has to be able either to resist damages caused by the accidental explosion of a small plastic landmine, or to be easily and rapidly repairable in the field. As it is low-cost, even damages associated with the accidental explosion of a fragmentation mine should not be too costly to be repaired.

Each machine can be considered a semi-autonomous system, helping a single deminer in his work, and a certain number of machines can be controlled to perform area-reduction operations, working as a multi-agent system.

4.4. Design preliminary choices and model set-up

Pursuing the idea of employing mature technologies already available in the country and particularly small agricultural technologies, as basic machine, first I verified the suitability of the power tiller as tractor unit.

Between the main reasons leading to the idea of using the power tiller, there were its small dimensions and its low weight. In order to process the ground in front of a deminer, the machine has to work in the demining lane, which in Sri Lanka is 1200mm wide: 100mm on each side are used for verification of working depth. In order to be transported easily to the minefield, the machine has to fit in the boot of the small ISUZU ELF trucks mostly used by NPA, carrying up to 2000 Kg in 1,8 x 5m area. The weight and dimensions of one of the biggest powertiller available on the Sri Lankan market, produced in China by the Dongfeng Brand, the DF-12L model with 10kW engine are more than suitable.

The powertiller shown on the right hand side of fig. 4.11 is the one we have in the laboratory, on which we are working. It was produced in Italy in 1944 and presents similar characteristics to the one we would like to employ in Sri Lanka. We bought it second hand for 100€. After some work, it started running again.

Obviously, the speed of work of a power tiller is higher than the one of a manual deminer, calculated during time and motion studies held for the EUDEM2 survey equal to 0,0037 m/s. The working speed of a power tiller processing the ground with a milling tool can be considered equal to 0,2 m/s.

The cost of power tillers is low, especially in developing countries like Sri Lanka, where a 10kW one can be bought for €250, €70 if second-hand.

Overall dimensions:
L: 1900mm W: 770mm H: 850mm
Weight: 243kg
Travelling speed (I gear): 1.1km/h
Engine: 10hp
Differential: yes
Gears: 3 forward, 3 reverse
Possibility to reverse handler: no
Cost: 100€ secondhand

Overall dimensions:
L: 2680mm W: 960mm H: 1250mm
Weight: 350kg
Travelling speed (I gear): 1.4km/h
Engine: 12hp
Differential: yes
Gears: 6 forward, 2 reverse
Possibility to reverse handler: no
Cost: 70€ secondhand, 250€ new

Fig. 4.11. Power tiller in use at the University of Genova Vs Power tiller available in Sri Lanka.

The effective employment of a power tiller as tractor unit has to be evaluated considering functional requirements. Moreover, attention has to be paid at keeping the machine extremely simple, avoiding adding to a very simple basic unit such as the power tiller, complex modifications or tools.

Parameters have been identified that contribute to achieve extreme simplicity and effectiveness, referred at as *Simpleffectiveness*.

The features the tractor unit has to present in order to be Simpleffective are:

- forward/backward motion (traction)
- steering: 1m curve radius
- energy supply to end-effectors
- stability
- assessment of ground processing depth
- mine disposal
- safety of operator
- shock wave protection for machine (and operator, in manual use)

The machine has to be mine resistant: it has to be designed to be proof against anti-personnel (AP) blast mines, or easily and rapidly repairable in the field.

A first indicative analysis of the mobility and energy requirements suggested that the power tiller is suitable to the aim, with only little adjustments. In fact, power tillers present several gears, the number depending on the model, including at least one for going backward; steering can be achieved thanks to the differential gear. Moreover, part of the energy coming from the engine can be used for actuating the end-effectors through the power take off.

Generally, power tillers available in Sri Lanka do not have a battery on board; therefore one should be added to supply energy to the control unit. The scheme representing the distribution of energy between modules and control is reported in fig.4.12. A rough estimation of the power required pushing or pulling an end-effector to process the ground at 100mm depth, 1200mm wide, in clay soil, at 0,1m/s working speed is 3 kW. The power absorbed by a vegetation cutter tool 1200mm wide, like cutting bar, is 4 kW.

I have created a physical, a multi body and a 3DCAD model (fig. 4.13) to support design decisions, through simulations and tests. I first used the physical model in a preliminary test performed to get physical understanding of the effects of a mine explosion on the power tiller, when a mine is activated by one wheel.

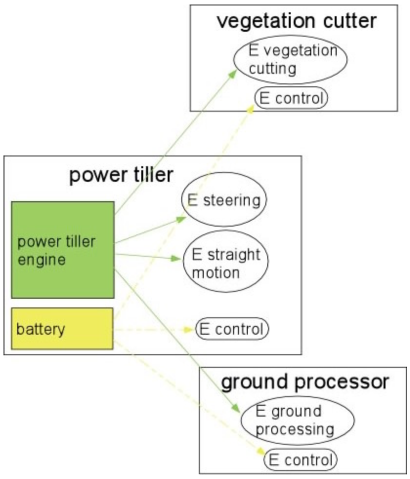


Fig. 4.12. Energy distribution between modules.

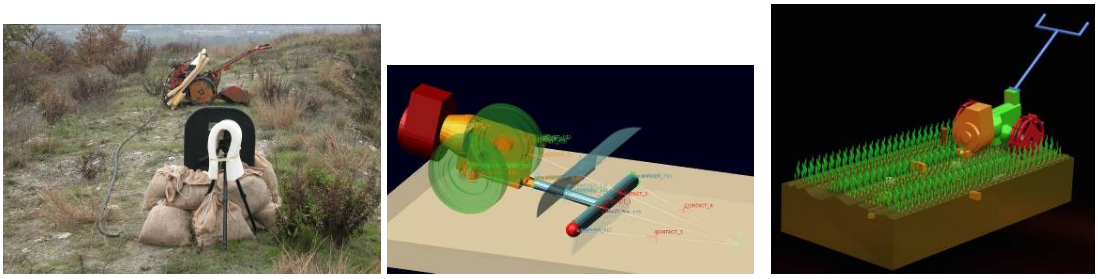


Fig. 4.13. Physical, multi-body and 3DCAD models of the machine.

4.5. First explosion test

The aim of the preliminary test was to see the effects of the explosion of a small plastic blast type landmine on a power tiller: to better understand the physical mechanism of the explosion of 50 g of TNT, to see the effects on the power tiller, to measure the acceleration on the wheel axis and to see the effects of the explosion on a dummy operator.

The test took place in a cave at open air near to Fornovo, Parma in Italy. It was made possible by the kind collaboration of Danilo Coppe, one of the major Italian experts in civil explosions, from the Istituto Ricerche Esplosivistiche (I.R.E.), Parma, Italy. Together with Danilo, some of my colleagues of the University of Genova kindly accepted to help me with the test, Matteo Zoppi, Vittorio Belotti, Roberto Pani, Paolo Silingardi e Mattia Salvi. They were researchers, students or technical assistants.

The system tested (fig. 4.14) was the powertiller on which later I developed the first machine prototype. It is an old commercial power tiller, developed in Italy by Pasquali approximately 40 years ago. Its type is Pasquali PL, the motor is ACME type VT88, it has a cubic capacity of 480cc and a power of 10HP. The power tiller had steel wheels 460mm in diameter and 120mm wide.

The end-effector mounted on the power tiller was a rotary tiller. The chassis is entirely made of cast iron between 6 to 8mm thick.

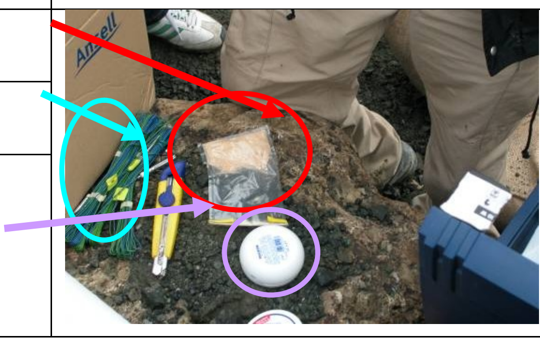
Fig. 4.14. Powertiller tested and details of structure.

Specifications	Dimensions
Length	~ 2000 mm
Width	~ 550 mm
Height	~ 800 mm
Weight	~ 250 kg
Ground Clearance	~ 160 mm
Maximum Speed	~ 10 km/h

Fig. 4.15. Powertiller characteristics.

Characteristics and approximate dimensions of the powertiller are reported in the table in fig. 4.15.

Materials used for testing is reported in the table in fig. 4.16.

Material type	**Picture**	**Quantity**	**Scope**	**Provided by**
TNT		50 g bag x 5 bags	explosive for mines	Danilo Coppe
detonators		5	detonators for mines	Danilo Coppe
plastic containers		5	casings for mines	UNIGE

power tiller		1	power tiller to be tested	UNIGE
dummy		1	highlight effects of mine explosion on power tiller operator	Danilo Coppe
accelerometer (and cables and laptop)		1	measuring acceleration on the wheel axis and on the handler of the power tiller	UNIGE
rake		1	Testing possible tool	UNIGE
video camera		1	documenting events	UNIGE

11 mm steel plate		1	testing possible armouring	Tecnospamec S.r.l.

Fig. 4.16. Material used for testing.

Soil was wet grey clay; soil surface was sparkled with small stones as it can be seen in the pictures taken. Weather was humid and cloudy. Temperature was around 12°C.

Before actual test could take place, we had to prepare “mines”. As proper mine casings were not available, I looked for small plastic containers approximately the size of real mines of type P4Mark1 and Type72: 70mm in diameter and 40mm high.

“Mines” were prepared (fig. 4.17) by placing the plastic bags containing 50 g of TNT inside the casing, after having cut a small hole in the bag to allocate the detonator. Before closing the casing and wrapping around adhesive tape, paper was compacted and added to fill the remaining space. Explosions were manually induced by Danilo, not by treading on mines.

Fig. 4.17. Preparation of a mine.

Results [4.11] were encouraging as the power tiller chassis was not considerably damaged after four explosions, suggesting that only a thin steel plate, possibly presenting small holes in order to lower its weight, could be used to protect it. Steel open cage wheels deformed after the explosion and lost lugs. We believe that damages to them were limited by their open structure allowing part of the blast wave to expand in air.

Detailed analyses of results of each explosion are reported hereafter.

4.5.1. Test n°1: white explosion

Aim

The Aim of the first White explosion was to verify that “mine” explosion was regular and similar to the one of real mines.

In order to make maximum use of resources available and do not waste one “mine”, I tested the effects of the explosion on the 11mm steel plate that could be used to protect the power tiller chassis. In order to have a better idea of the blast wave phenomenon I placed a package containing 1kg of flour over the “mine”; I wanted to quantify the extent of the blast wave, by measuring the radius around the charge where flour would spread.

Test bed

The test bed has been prepared burying the “mine” right under soil surface. A little hoe has been used to lift the soil in order to create the space necessary to allocate the “mine”.

Fig.4.18. “Mine” placement for the first test.

I considered this to be the worst case. In fact, while in the Vanni region in Sri Lanka mines are found buried up to 100mm, the worst blast effect happens when mines are near to the soil surface. When mines are buried deeper, once activated their blast wave travels through the soil and looses power on its way. A hoe similar to the one we used, is the tool generally employed to bury real mines. When they are buried they are generally near to the surface; after years they can move deeper because of soil movements, floods or other weather conditions which have occurred in the time passed. Over the “mine” I placed the 1kg package of flour; beside the “mine” I placed the steel plate. A stone has been use to support the steel plate.

Fig.4.19. Disposition of steel plate and flour package for the first test.

Results

The explosion was satisfactory. The “mine” assembly and the connection between the detonator and the initiator proved to be good. As results I found that the flour package disappeared and that the steel plate didn’t get damaged. The flour spread around the charge in a large area; the exact radius of the area turned out to be difficult to measure because flour particles were too similar to due drops still present on the vegetation. The area where flour spread was approximately 6m in radius. I believe that flour atomized after the blast wave together with the package; small parts of the package were found near the blast site.

The steel plate was not damaged. It only moved from the original position supported by the stone behind. Even if the plate faced the blast wave in the best position, 90°, we believe that a protection of 11mm steel plate for the power tiller chassis is far more than enough.

Fig.4.20. Test n°1: crater of the explosion
(each segment of the metre is 20 cm long).

The crater made by the explosion was approximately 50 cm in diameter and 15 cm depth.

4.5.2. Test n°2: landmine under left wheel

Aim

The Aim of the second test was to verify if the power tiller could keep on working after having endured an accidental explosion. I measured the acceleration on the wheel axis and I observed the effects on the chassis and on the wheel after the explosion of the mine underneath. I was looking for wheel deformations and chassis resistance to damages caused by the explosion.

Test bed

After burying a “mine” right under soil surface, as in the previous test; we placed the left wheel of the power tiller right over it.

The accelerometer was placed on the wheel axis as near as possible to the left wheel standing over the “mine” in order to measure forces on the tiller’s axis.

Fig.4.21. Accelerometer on the wheel axis.

In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed layers of wood 250mm thick and foam rubber 50mm thick between the wheels and the engine.

A camera, protected by a Kevlar shield, placed 7m away from the place of explosion has been used to record the whole dynamic of explosion and to see eventual tiller movements which could be dangerous for the deminer driving the machine.

Fig.4.22. Disposition of power tiller and camera for the second test.

Results

Explosion raised the left wheel of about 300mm. The crater made by the explosion was approximately 500mm in diameter and 250mm depth; this was deeper then the crater made by the white explosion. The reason could be that this time the blast wave was not free to propagate towards the high. The left wheel standing over the "mine" has been seriously damaged by the explosion. The blast wave determined the separation of three lugs from the wheel; lugs were found near by the wheel. The wheel has also been deformed, part of wheel frame got in contact with the chassis preventing the wheel to rotate. The chassis has not been damaged. Layers of wood and foam rubber protecting the engine have not been damaged as well, resulting intact after the explosion.

Fig.4.23. Damages on the power tiller chassis and left wheel after the second test.

The accelerometer placed on the wheel axis worked well. I was able to record the whole explosion event from the initiation, the detonation to the exhaustion of the whole process.

Unfortunately, the accelerometer I employed was able to measure accelerations within the range of -50 g, +50 g. The accelerations recorded were higher; therefore results obtained with the sensor can only give a qualitative measure of the explosion event. In order to obtain a correct measure of the accelerations occurring on the wheel axis after an explosion I need to employ an accelerometer with higher range.

From the results obtained I can anyway extrapolate some important information regarding the explosion.

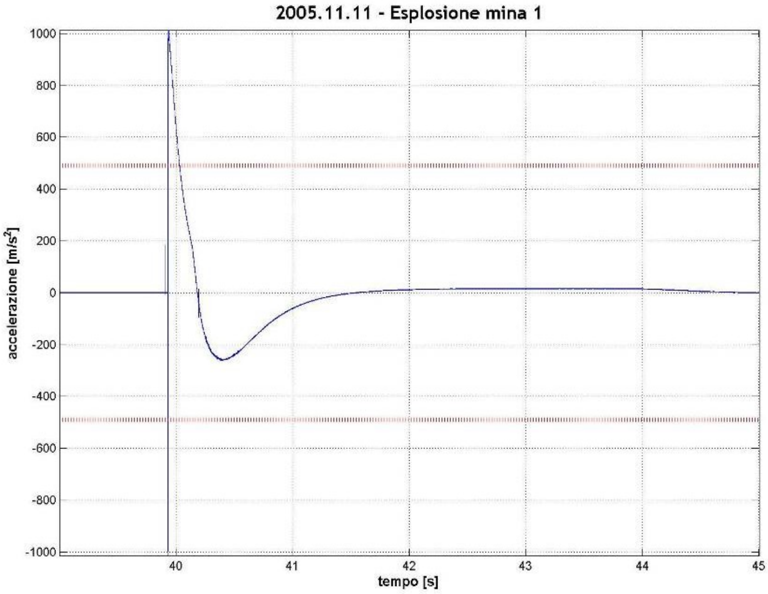


Fig.4.24. Acceleration versus time during the whole explosion process.

Values of accelerations exceeding the red band are not reliable; when acceleration over passed the range limit, the sensor saturated.

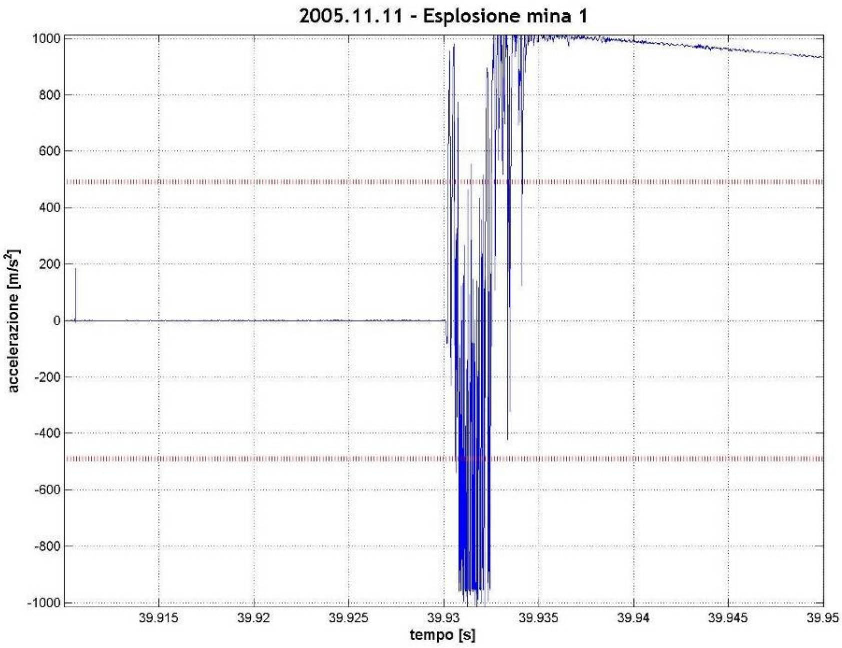


Fig.4.25. Zoom on the acceleration versus time during time between 39.91 and 39.95 second.

From Fig.4.25 the acceleration on the wheel axis due to the detonation of the charge can be distinguished from the acceleration due to the explosion itself.

The short vertical line occurring around 39.91s, is the acceleration due to the detonation. It reaches the maximum value of approximately 200m/s^2. The next vertical line occurring around 39.93s, is the first acceleration recorded due to the explosion; it is oscillatory as the power tiller structure reacts vibrating to the blast wave impulse. The maximum value of acceleration reached by the wheel axis due to the explosion was not recorded because it exceeded 50g (= 490 m/ s^2), the maximum value measurable with the accelerometer employed.

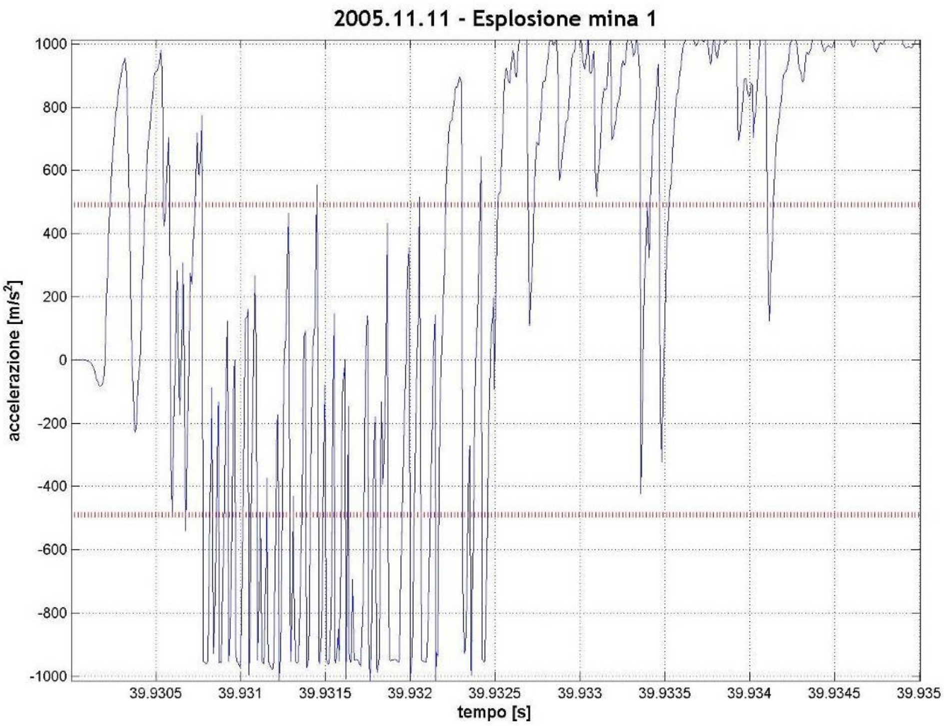


Fig.4.26. Zoom on the acceleration versus time during time between 39.93 and 39.935 second.

The explosion happened 0,02s after the detonation. The whole explosion process lasted approximately 0,005s, as after this time acceleration on the wheel axis decreases continuously, until it arrives to 0m/ s^2 and the power tiller starts falling down.

4.5.3. Test n°3: landmine under left wheel and dummy

Aim

The aim of the third test was to investigate the effects of the explosion of a mine under a wheel on the power tiller operator.

I also wanted to check the reaction of the left wheel and chassis after more than one explosion. I measured the acceleration on the wheel axis and I observed the effects on the dummy operator, on the chassis and wheel after the explosion of the mine underneath. I was looking for harm to the dummy, wheel deformations and chassis resistance to damages caused by the explosion.

Test bed

After burying a “mine” right under soil surface, as in previous tests; we placed the left wheel of the power tiller right over it.

Fig.4.27. “Mine” placement for the third test.

The accelerometer was placed on the wheel axis in the same place of the previous test.

The dummy was placed at a distance of 2m from the “mine”, where the deminer is supposed to be while using the tiller.

In fact, this is the distance currently used in the Standard Operational Procedures (SOP’s) adopted by the Norwegian People’s Aid (NPA). Deminers use different types of common rakes to break up the ground and to move the loosened soil to check for the presence of landmines: all rakes have a handle 2 m long. This distance is considered enough safe for the operator to be from the mine in case of an accidental explosion.

I placed a cardboard panel in front of dummy’s legs in order to detect little stones or other material that could harm the operator, if thrown by the explosion. Moreover, I have covered dummy’s eyes with tape to allow the detection of anything that could have hit the eyes during the explosion.

In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed layers of wood 250 mm thick and foam rubber 50mm thick between the wheels and the engine.

A camera, protected by a Kevlar shield, placed 8m away from the place of explosion has been used to record the whole dynamic of explosion and to see eventual tiller movements which could be dangerous for the deminer driving the machine.

Fig.4.28. Disposition of power tiller and camera for the third test.

Results

Explosion raised left wheel of about 300mm. The crater made by the explosion was approximately 650mm in diameter and 300mm depth, similar to the one made by the previous explosion.

As predictable result the left wheel standing over the “mine” has been damaged more seriously than in the previous test: it lost other three lugs and the circular structure holding lugs broke. This could be due to the fact that the wheel had already been weakened by the first explosion.

The chassis has not been damaged although the layers of wood and foam rubber protecting the engine have been damaged probably under the weight of the power tiller falling down.

The dummy didn’t present any damage caused by the ejection of soil particles at high speed during the explosion. No signs were found on the dummy’s body, or on the tape used to cover its eyes. I have found only small signs of particles hitting the cardboard. This could be due to the fact that power tiller body and tools worked as shield for the operator

Fig.4.29. Damages on the dummy, power tiller chassis and left wheel after the third test.

The accelerometer placed on the wheel axis did not worked well this time. I was not able to record the explosion event.

4.5.4. Test n°4: landmine in front of powertiller

Aim

The aim of the fourth test was to verify if an end-effector similar to the rake would be able to stand the explosion of a mine activated by the end-effector itself. I also wanted to see effects of mine explosion on the operator when a mine explodes in front of the tiller, activated by the end effector.

Test bed

After burying a "mine" right under soil surface, as in previous tests, I planted the rake next to it into the ground in front of the tiller.

Fig.4.30. Disposition of rake for the fourth test.

A cardboard panel was placed in front of dummy's legs in order to detect little stones or other material that could harm the operator, if thrown by the explosion.

In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed layers of wood 250mm thick and foam rubber 50mm thick between the rake and the power tiller.

Fig.4.31. Disposition of power tiller and rake for the fourth test.

Results

Explosion damaged the layers of wood and foam rubber placed between the rake and the power tiller to protect the machine. The crater made by the explosion was approximately 500mm in diameter and 270mm deep, similar to the one made by the previous explosion.

As result the rake has been damaged: tines deformed expanding wider. The power tiller was not damaged. The dummy didn't present any damage caused by the ejection of soil particles at high speed during the explosion. I didn't find any sign on the dummy's body, nor on the tape used to cover its eyes. I found only small signs of particles hitting the cardboard. This could be due to the fact that power tiller body and tools worked as shield for the operator.

Fig.4.32. Damages on the rake after the fourth test.

4.5.5. Test n°5: landmine under right wheel

Aim

The aim of the fifth test was to verify if the operator would be harmed by the acceleration transmitted by power tiller handlers after an explosion under the wheel. I measured the acceleration on the handle bar.

Test bed

After burying a "mine" right under soil surface, as in previous tests, we placed the right wheel of the power tiller right over it. In this case, we found a big stone under the ground; I decided to place the "mine" over the stone in order to see the effects of the explosion when the blast wave does not have the possibility to expand downward.

The accelerometer was placed on the handle bar in order to measure the accelerations transmitted to the operator. Unluckily, we didn't prepare a proper support for the accelerometer as the idea to test the acceleration transmitted to the operator arms came when I was already in the test field. We tried to arrange a way to fix the sensor as firmly as possible to the handlebar; we used glue and we strengthened the link using electric cables.

A cardboard panel was placed in front of dummy's legs in order to detect little stones or other material that could harm the operator, if thrown by the explosion. In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed layers of wood 250mm thick, foam rubber 50mm thick and the steel plate used in previous tests 110mm thick, between the wheels and the engine.

Fig.4.33. Arrangement of the accelerometer on the handle bar.

Results

Explosion raised the left wheel of about 300mm. The crater made by the explosion was approximately 600mm in diameter and 230mm deep; this was larger then the crater made in previous tests. The reason could be that this time the blast wave was not free to propagate downward, due to the presence of the stone. The right wheel standing over the “mine” has been damaged by the explosion. The blast wave determined the separation of one lug from the wheel; the lug was found near by the wheel. The wheel was also deformed.

The chassis was not damaged. Layers of wood and foam rubber protecting the engine moved from the original position, also because they were already damaged by previous explosions and therefore not precisely positioned at the beginning. The steel plate didn’t get damaged but moved from the original position together with the other protection layers.

Power tiller was found in oblique position. The effect of explosion of the “mine” over the stone has probably been stronger than the one of previous tests. In fact, I found more signs of particles hitting the cardboard. Unfortunately, the accelerometer did not work properly.

Fig.4.34. Damages on the power tiller right wheel and cardboard after fifth test.

4.5.6. Conclusions

Test results were promising. The powertiller, with only little protection, withstood four explosions reporting no serious damage. In fact, after testing we could still start the engine and drive it away from the test site, on its wheels, even if not properly rounded anymore. In fact, wheels got the major damages: several lugs were lost and rims lost their original rounded shape. Before driving the powertiller again we needed to hammer them.

I could notice secondary damages on the chassis only after some time, when the powertiller was stationed back in the laboratory. Damages were limited to the left side, where the accelerometer was placed, and where the explosion occurred; here one of the four bolts coming out of the axle, to which the wheel is fixed, lost his head and could be unthread from the chassis. I could not notice any damage to the drive train, but as the bolt head was probably lost due to some mechanical vibration induced by the shock waves, if the powertiller has to be redesigned to be driven repeatedly over landmines, i.e. carrying a ground processing tool at the back, a kind of protection for the drive train should be devised.

Anyhow, it has been proven that, even with no protection, the powertiller could be driven over few landmines without getting too much damaged. Therefore, the powertiller seems a good choice as prime mover for demining tools in areas where only small plastic landmines are known to be. Even with no or limited protection, such as metal shield for preventing small stones to damage delicate parts such as the engine, it might be used for clearing vegetation in low density contaminated areas, without previously or simultaneously removing landmines from the lane.

In fact, a thin steel plate, possibly presenting small holes in order to lower its weight, could be used to protect the chassis, when power tillers newer than the one I used will be employed; generally new models of power tiller present more weak parts than the older models.

Steel wheels adopted are not a good solution as they deform after the explosion and they loose lugs. On the other side they allow the blast wave to expand in the air in between the structure; damages are limited because part of the power of the blast is lost in the air. Therefore, stronger open cage wheels could be good.

Before thinking about an operator driving the machine in the minefield, accelerations transmitted by the handler to the operator’s arms, when a mine is activated by the power tiller wheel, should be effectively measured. Anyhow, external damages on the dummy were limited to the possible harm caused by the small soil particles hitting the cardboard panel ejected at high speed by the blast wave. Therefore, if a device to block the shock wave from damaging the operator arm is devised, I believe that a shield covering the lower part of the body could be enough to protect the operator, obviously wearing proper personal protective equipment.

4.6. Implementation plan

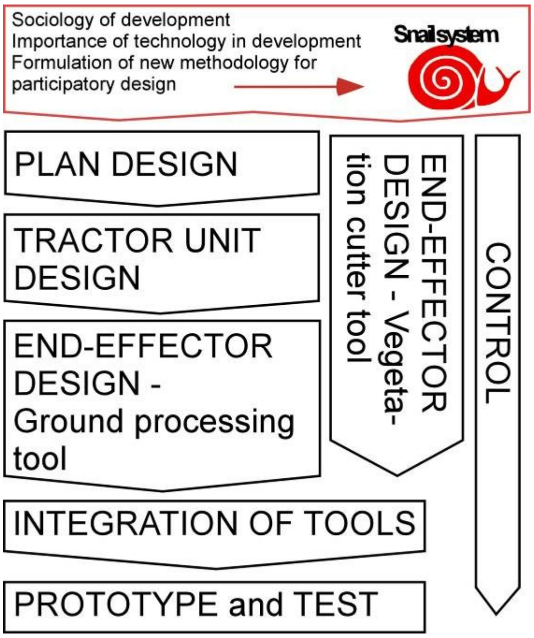


Fig. 4.35. Implementation plan

A modular top-down design approach was chosen. Starting from the task, defined by deminers, the mechanical modules able to accomplish the work were conceived. The project involves the mechanical design of three modules: tractor unit, ground processing tool and vegetation cutting tool (not included in the thesis but available on the website).

The project foresees also the implementation of the control of the machine that needs to be operated remotely, when Unexploded Ordnance (UXO) and fragmentation Anti Personnel (AP) mines are known to be present.

The overall essential requirements the machine has to satisfy are:

- reliability: 100% clearance
- safety of operator: 100%
- depth of demining: 100 mm
- width of clearance: 1200 mm
- speed of clearance: higher than manual
- types of mines: small plastic blast-type AP mines
- cost: 20.000 €
- remote control distance: 20 m

Considered mines are small because they are between the less harmful existing ones, containing up to 50g of explosive only. The machine is designed to resist damages caused by AP blast mines or to be rapidly repaired after such explosions. UXO and fragmentation mines are also present, but only in certain known minefields, where the machine should not be used.

Cost is one of the main points of the project, being one of the major causes of poor adoption of machines into demining programmes. The price of €20.000 includes the research and developing cost and is equally divided between the modules and the control.

Chapter 5 Tractor unit

- Design preliminary choices: working configuration
- Breakable connection design and development
- Second explosion test
- Ideas on tractor unit redesign

5.1. Design preliminary choices: working configurations

The tractor unit is the core module of the machine.

Having proved that the powertiller is a good prime mover on which to base the tractor unit, before starting the design around it, it was necessary to define what the task is and what the requirements the tractor unit has to satisfy are.

The tractor unit has to provide support to the ground processing tool and to all the other tools that might be designed in the future to tackle other demining tasks: it has to be a moving platform with good out track capabilities, with enough traction and mobility on uneven not structured terrain. It has to be stable and provide sufficient energy, both in terms of drawbar power, and of general power supply, to the modules connected to it, and, moreover, it has to be safe for the operator who drives it. Because dealing with landmines, the tractor unit should also be designed to resist damages caused by shock waves.

Being the core module of the machine, these are the same functional requirements applicable to the whole machine, previously referred to as *Simpleffectiveness* parameters.

- forward/backward motion (traction)
- steering: 1m curve radius
- energy supply to modules
- stability
- assessment of ground processing depth
- mine disposal
- safety of operator
- shock wave protection for machine (and operator, in manual use)

Giving that remote control was developed to allow the driver to be at safe distance, and the machine to be more versatile, if measurement on the handler can take place and a device isolating dangerous vibrations can be developed, where UXO are known not to be present, the tractor unit could also be driven manually. Therefore, while developing remote control, leverages allowing manual control were not removed. Dual control will always be possible.

Together with *Simpleffective* functional parameters, the tractor unit has also to respond to the cost-efficient life-cycle design paradigm (fig.2.7). It has to be low cost, simple and easy to manufacture, assembly, disassembly, use and maintain.

In terms of quantitative requirements, the tractor unit has to be:

- light: < 1000kg, allowing the ground processing tool module and the other possible modules to be all together 1000kg and not overcome the limit of 2000kg (the maximum the truck boot can support)

- small: supporting a ground processing tool 1200mm wide (demining lane width), and being not longer than 5m (length of truck boot)
- low-cost: < 5000€, including research and development cost
- low-speed: it is sufficient for it to be > 0.0037m/s (manual speed)
- powerful: > 7kW (3kW for ground processing tool and 4kW for vegetation cutting tool)

The main tractor unit design choice was on the working configuration. In fact, while the vegetation cutting module, when needed, has to be placed on the front of the power tiller to allow the machine to pass through thick vegetation, two different possible working configurations for the ground processing tool, designed to rake the ground and bring mines up on soil surface, have been identified: one with the ground processing tool at the back (G-P-B) and one with it on the front (G-P-F).

In the first case, with Ground Processing tool at the Back (GP-B), the end-effector would rake and lift mines up after the machine has passed. Therefore, the tractor unit should be protected from blasts of mines activated by the machine itself when it passes over contaminated ground.

The machine could be used for different applications at different times: for raking or for cutting vegetation. As vegetation has to be cut before the machine passes, either the vegetation cutting tool should be mounted at the front and the ground processing tool at the back, or if using the same hitch for both modules, they should be used at different times (fig.5.1).

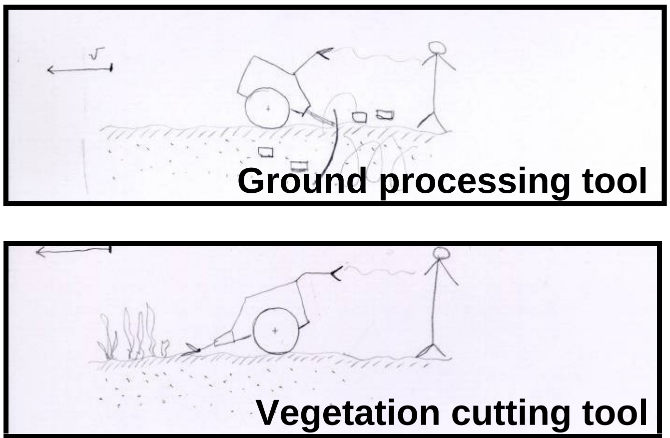


Fig.5.1. Ground Processing tool at the Back (G-P-B) working configuration.

In the second case, with Ground Processing tool at the Front (GP-F), the end-effector would rake and lift mines up before the machine passes over the ground, so that the tractor unit would not need to be blast resistant, it only would need to be protected against secondary damages due to accidental explosion caused the by the tool in the front. The vegetation cutting module should be integrated with the ground processing tool (fig. 5.2).

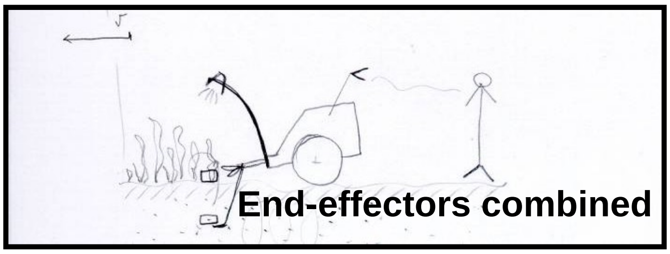


Fig.5.2. Ground Processing tool at the Front (G-P-F) working configuration.

The choice influences tractor unit performance and simplicity. Therefore, it is subject to the evaluation of *Simpleffective* parameters values in the two cases.

I prepared a matrix (fig. 5.3) reporting “plus” (advantages) and “minus” (drawbacks) related to each parameter for the two configurations. I completed it by adding other two columns reporting “known effects” and “possible improvements” for both the configurations.

Looking at the matrix and following the idea of modifying the powertiller as little as possible, I choose to work first on a blast protection allowing the tractor unit to drive over landmines freely. Having a blast resistant tractor unit would allow to work with the Ground Processing tool at the Back (GP-B), which is more natural as it is the way the plough is pulled by horses, and there would not be need of tracks or any other means for increasing traction; moreover, the tractor unit would be a much more versatile platform, with different modules usable independently. Even the vegetation cutting tool could be driven by the tractor unit on its own.

Therefore, first I investigated how the powertiller could be protected from blasts and how much it would cost.

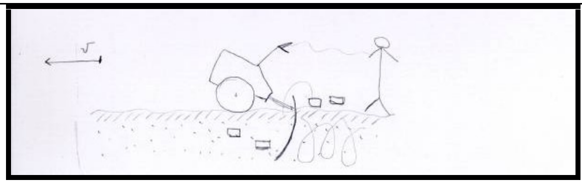
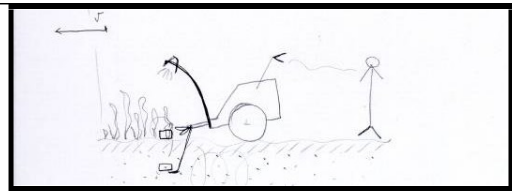
	 GP-B				 GP-F			
Parameters	**Advantages (+)**	**Drawbacks (-)**	**Known effects**	**Possible improvements**	**Advantages (+)**	**Drawbacks (-)**	**Known effects**	**Possible improvements**
Forward/backward motion	Wheels pass on compact soil	Wheels pass over buried landmines	Vibrations might affect drive train	Need of blast protection	Wheels pass on cleared ground	Wheels pass over loose soil	reduced traction	Use of tracks, increase weight
Steering	-	-	-	-	-	-	-	-
Energy supply	-	-	-	-	-	-	-	-
Stability	Natural way to work					Need of weight transfer mechanism	Tendency to dig into the ground	Use of ballast
Assessment of ground processing depth	-	-	-	-	-	-	-	-
Mine disposal	Mines left on machine lane					Mines have to be moved from lane		
Shockwave protection		Heavy protection essential			Only need of light protection			

Fig.5.3. Matrix for choosing working configuration.

5.2. Some blast protection ideas and breakable connection design

The energy released during the detonation of an explosive charge, driven by the shock wave within the ambient, is transmitted to all what is found on the way. The shock wave is the extrinsic phase of a detonation, caused by the interaction between the products of the explosion with the ambient; it takes place when explosive materials are all extinguished. As previously said (paragraph 2.1.1), the shock wave contains approximately 50% of the energy originally contained in the explosive charge.

A wave can be generally defined as a disturbance, or an energy transport phenomenon, which progresses from one point in a medium to other points without giving the medium as a whole any permanent displacement. The speed at which the wave propagates through a material medium (solid, liquid or gas) depends on the elastic and inertial properties of that medium.

When the medium around the charge is air, the shock wave is called blast wave. Air is a special fluid because of its low density and high compressibility.

Near to the charge, the blast wave is composed by a front of compressed air followed by the gases produced by the explosive reaction. The percentage of compressed air increases with distance from the charge: at a distance equal to 14 times the charge radius, the blast wave contains only compressed air and it propagates autonomously, without gases propelling it from behind (fig. 5.4.).

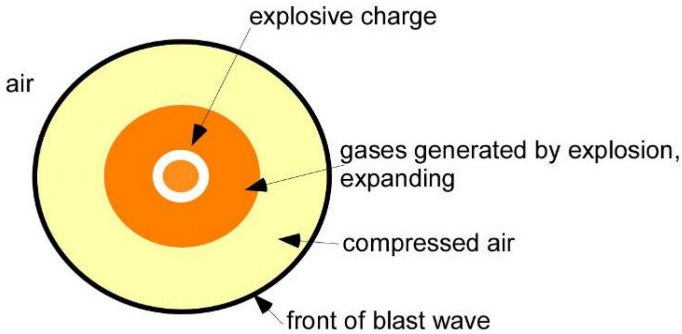


Fig.5.4. Blast wave: first instants of extrinsic phase of an explosion (adapted from Petralia, S. [5.1]).

The pressure recorded by a transducer placed at a certain distance from the explosive charge, when it is invested by a shock wave, is decreasing with time (fig. 5.5) with an almost exponential curve. After a peak static overpressure (p_s), which is the pressure associated with the front of the blast wave, the pressure of compressed air, passing right after, is constantly decreasing until it reaches the atmospheric level (p_o). As cooling and expansion continue, pressure falls a little below ambient atmospheric levels; this occurs because the velocity of the gas particles causes them to over-expand slightly before their momentum is lost. Pressure eventually stabilizes on the atmospheric level again.

t_a is the arrival time of the pressure pulse to the transducer, T is the period or time length of the positive phase of the pulse.

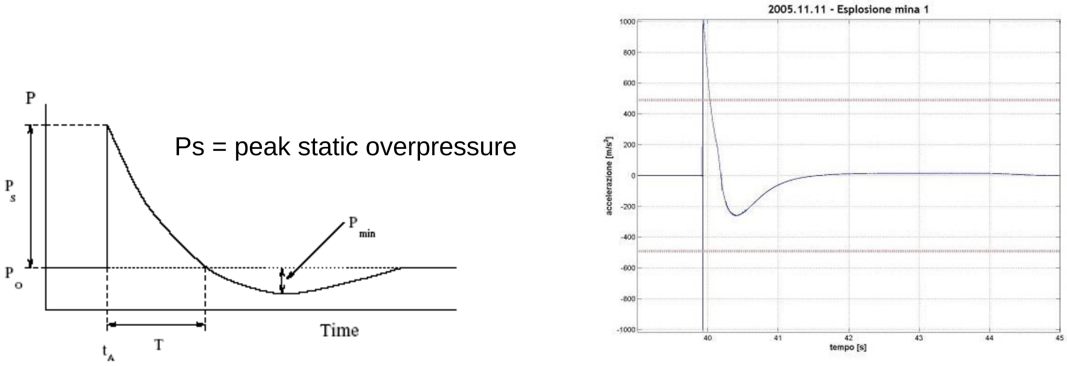


Fig.5.5. Pressure versus time of a blast wave, seen by a pressure transducer fixed in space. Acceleration versus time recorded with accelerometer on the powertiller axle, during test (paragraph 4.5.2).

It is interesting to see that a very similar curve was recorded by the accelerometer placed on the powertiller axle during the first test, described in paragraph 4.5 and reported in fig. 5.5.

There are several sets of overpressure equations developed using both numerical and experimental techniques. A set was developed by Brode in the 1950s. One equation (eq.5.1) applies to the near field, where pressure is over 10bar (1bar = 10^5Pa) and one (eq.5.2) is given for the medium and far field, where pressure is between 0.1 and 10bar.

$$p_S = \frac{6.7}{Z^3} + 1[bar] \tag{5.1}$$

$$p_S = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019[bar] \tag{5.2}$$

Where, Z is the scaling factor. Since the same overpressures will be generated by different weight explosives, the weight of the charge can be combined with distance from the charge to create a scaled parameter. This is the scaling factor Z given by eq.5.3.

$$Z = \frac{R}{w^{1/3}} \tag{5.3}$$

Where, R is the distance from the centre of the explosion given in meters and w is the equivalent weight of TNT given in kilograms. The equivalent weight of TNT, w, is obtained by multiplying the mass of explosive considered by a TNT equivalence factor that is reported in tables [5.2].

Generally, a blast wave is characterized by:

- high pressure (i.e. 13.6bar at 1.7m from 3kg of TNT charge)
- supersonic speed of propagation
- the wave compresses and heats the medium it flows through an irreversible process, the front of the wave acts as a discontinuous surface (a jump of state variables from immediately ahead to behind)
- the wave looses energy while traveling (fig. 5.6)

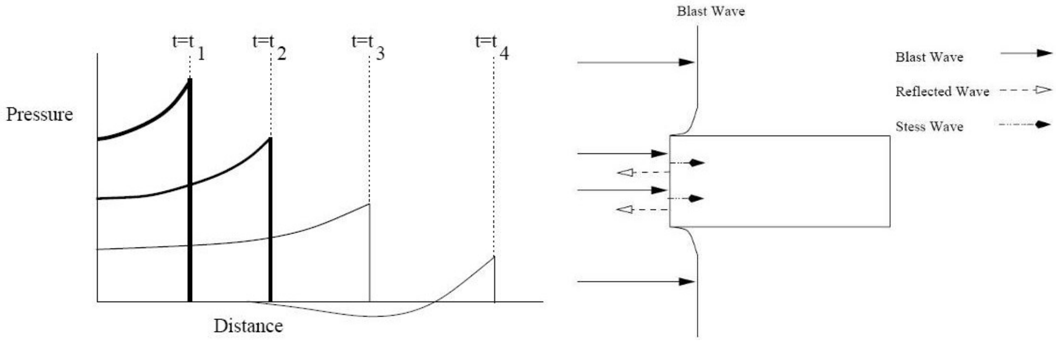


Fig.5.6. Pressure versus distance, seen by different transducers at different distances. Blast wave striking a rectangular object (source: Neff, M [5.2]).

The above treatment applies to explosion in air; when an explosive charge is on ground surface the overall energy transported by the wave is 1.8 [5.2] times more the total energy transported in air. This is due to the fact that the earth acts like a reflector. If it was a perfect reflector, i.e. the ground would not absorb part of the energy, the multiplying factor would be 2, as the overall energy would be driven through half of the space, 180° upwards.

When a blast wave invests a solid structure will generate a pressure on the face of the structure which is greater than the peak static overpressure of the wave. This occurs because the forward moving air molecules are brought to rest and further compressed by the collision. When an object is hit by the blast wave, it faces the peak static overpressure as well as the pressure associated with the particle being carried with the stream (fig. 5.6). For a wave investing a structure perpendicularly, normal reflection, the peak reflected pressure p_r is given by eq. 5.4.

$$p_r = 2p_s + (\gamma + 1)q \qquad (5.4)$$

$$q = \frac{1}{2}\rho u^2 \qquad (5.5)$$

Where, ρ is the is the air density immediately behind the wave front, u is the particle velocity and γ is the ratio of specific heat at constant pressure to specific heat at constant volume, for air γ =1.4. Therefore, for air, eq.5.6 can be derived, where p_0 is the atmospheric pressure.

$$p_r = 2p_s \frac{7p_0 + 4p_s}{7p_0 + p_s} \quad (5.4)$$

The behavior is complex and depends on the geometry of the object, the angle of incidence and the power of the wave. Generally, it can be observed that the pressure the blast wave generates when it hits an object is more than two times the peak static overpressure of the wave, p_s, and that p_s decreases as the distance from the charge increases. This happens because, although the total energy is preserved, some is spent to heat the medium in which the wave travels. Depending on the medium the wave passes trough, and on its elastic and inertia properties, the wave propagates differently. The velocity of propagation is directly proportional to the speed of sound, depending on the elasticity and inversely to the density of the medium.

If the tractor unit will work with Ground Processing tool at the Back (GP-B), at tractor unit passage wheels are likely to actuate landmines. The first idea I investigated was a device able to absorb part of the energy transported by the blast wave before it could reach the most delicate part of the powertiller, the drive train.

As they are in direct contact with ground and with possible landmines, I first thought about modifying wheels.

Generally, shock absorption systems available on the market tend to dissipate kinetic energy by transforming it into thermal energy, through different forms of friction. They can generate external friction such as dry friction brakes, or internal friction, as in the case of systems employing visco-elastic fluids or otherwise elastic materials that rebound with less force than was required to deform them, presenting the phenomenon of hysteresis.

Looking at low-cost shock absorption systems available on the market I considered with attention steel cable isolators. They are typical hysteretic damping devices, simply constituted by stranded wire rope, wound in the form of a helix and held between metal retainers (fig. 5.7). They adopt stranded wire rope as the elastic component and utilize inherent friction damping between the strands of the wire rope.

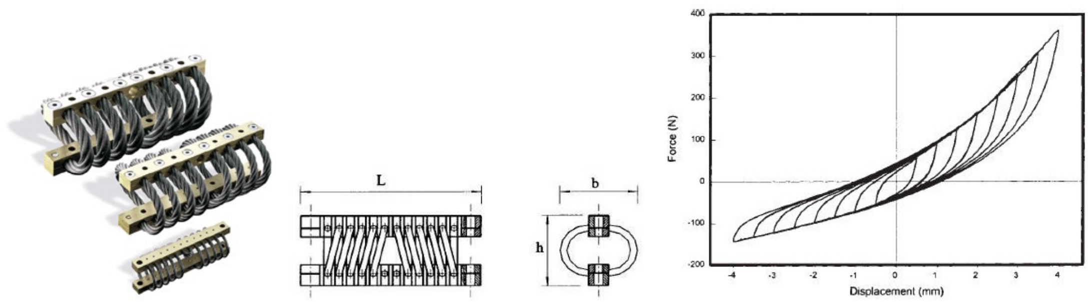


Fig.5.7. Steel cable isolator. Panflet, model and measured hysteresis loop from tension-compression cyclic loading test (source: http://www.globalspec.com/FeaturedProducts/Detail/Enidine/Wire_Rope_Isolators/43293/0 and Ni, Y. Q[5.3]).

The first idea I had was to employ stranded wire rope to isolate the axle and therefore the powertiller drive train to the rest of the wheel, rim and tire, as shown in fig.5.8, representing the 3D CAD model of the conceptual design of a possible wheel for the tractor unit. Similarly to cable isolators, the stranded wire rope is wound in the form of a helix between the hub of the wheel to be connected to the powertiller axle and the rim, on which the tire and the tube have to be mounted. A similar concept, of a wheel embedding a shock absorption system in its structure, has been developed by NASA in the realization of the wheels for the MER rover robot sent to Mars to collect geological samples (fig. 5.8).

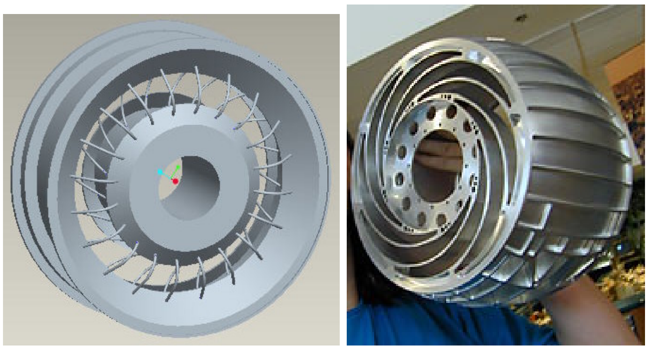


Fig.5.8. Conceptual design of a wheel for the tractor unit, embedding stranded wire rope for shock absorption. MER rover wheel (source: http://www.2020hindsight.org/2002/09/22.html).

Before starting the detail design I considered other possibilities. In second instance, I investigated practices already used in mine action to protect vehicles from landmine blasts. The Study of Mechanical Application in Demining, published by the GICHD, states that a simple and cost-effective manner to absorb energy is to fill the tires of wheeled vehicles with water. As it is a very simple and low cost practice, which has proven to work in many occasions, I tried to understand better why.

The first argument in favor of the use of water is that, while traveling, the shock wave passing through water looses more energy that the same wave in air, due to the higher thermal conductivity of the liquid. In fact, the energy transferred by heat conduction is proportional to the temperature gradient between the wave and the medium and to the thermal conductivity of the medium; energy transferred to water at the same ambient temperature than air, is higher.

The second consideration is that due to higher density of water with respect to air, the mass of water occupying the same volume, the tire, is much higher than the mass of air. As the speed of the shock wave front is proportional to the speed of sound in the medium, and, at same temperature, the speed of sound in water is much higher than in air, in water, the shock wave tends to be faster. Therefore the kinetic energy needed to move water particles out of the tire, due to the high pressure exerted on the tube by the wave, is higher than the kinetic energy needed to move air particles. This kinetic energy is taken away from the energy transported by the shock wave.

Therefore, I thought about another possible design of wheel for the tractor unit, in which not only the tire is filled in with water but also part of the structure to increase energy absorption. The conceptual design is shown in fig.5.9, where the light blue indicates water, contained in an appropriate container. Holes allow water to get out from the structure and therefore kinetic energy to be lost.

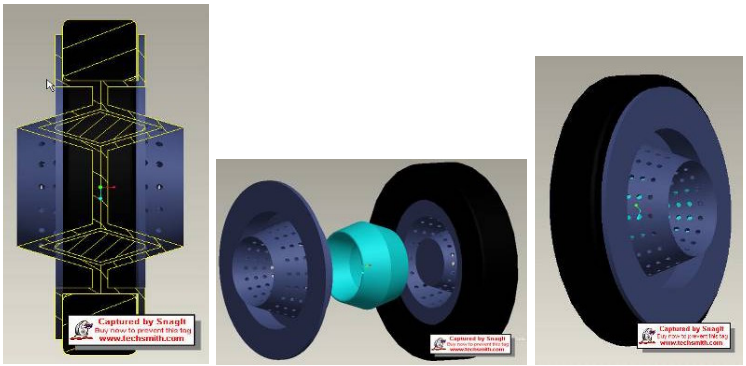


Fig.5.9. Conceptual design of a wheel for the tractor unit, with tire and frame filled in with water.

Before proceeding to the feasibility study and the detailed design, I considered another idea, already exploited in the armoring of mine protected vehicles, such as the South African Casspir, the development of a breakable connection to interpose between the wheel and the axle, to allow physical detachment in case of explosion under the wheel.

As this was the simplest and cheapest option, allowing to modifying the power tiller as little as possible, I investigated it further. The idea was that if physical connection was interrupted, the shock wave transmission to the axle and to the power tiller drive train should be significantly reduced. Moreover I believed that damages to the wheel should have been reduced as well.

Therefore, I started designing a breakable connection made out of brittle material, to be placed between the wheel and the axle capable of withstanding normal working load conditions while breaking when an explosion occurred.

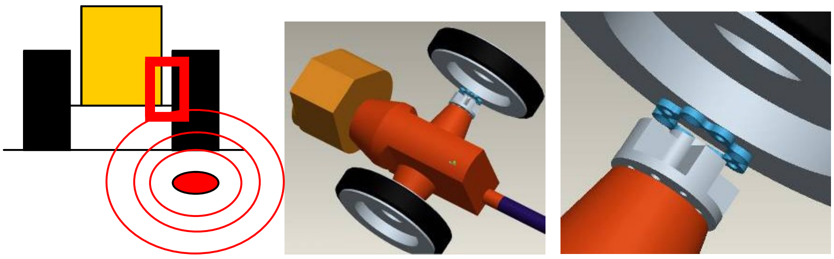


Fig.5.10. Conceptual design of breakable connection for the wheel.

To connect modern wheels to the axle of the old power tiller I have in the laboratory I had to design a supporting flange. The breakable connection is therefore designed to be fastened to the flange connected to the axle on one side and to the wheel on the other side (fig.5.11).

The breakable connection (fig.5.11) presents 8 holes, of which 4 are cone shaped to host counter sunk head M12 screws, used to fasten the connection to the flange, and the other 4 are simple holes hosting hexagonal head M12 bolts, used to fasten the connection to the wheel. The connection is 8mm thick and is shaped like a ring. In order to weaken the structure to favor failure in case of explosion, material between the holes has been reduced.

In case of explosion and fracture of the ring, most likely to happen along the bridges, a new ring could be replaced simply by screwing it into the flange first and into the wheel later.

The breakable ring is designed to be made of cast iron ASTM 30 class.

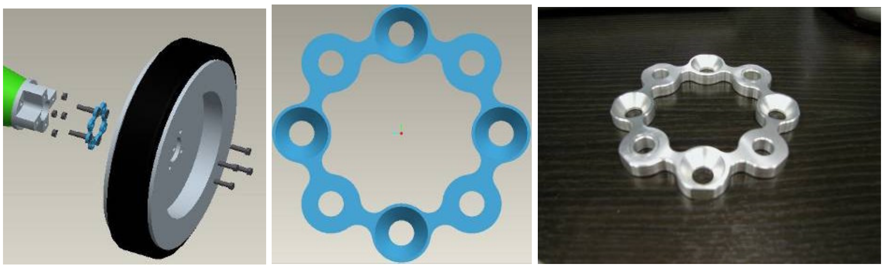


Fig.5.11. Assembly of wheel, breakable ring and flange; 3DCAD model of breakable ring and prototype.

Before prototyping the breakable connection, I have used the 3DCAD model in fig.5.11 to perform structural preliminary analyses, using the Finite Element Method (FEM). Importing the geometry into the FEM package of the pro-Engineering software it is possible to assign mass properties to the model, apply loads and constraints and run static analyses to see the stresses and deformations occurring in the model when loaded. I verified if the ring would break under load caused by explosion under the wheel, while resist normal working load conditions. Using the model shown in fig. 5.12 I calculated forces acting on holes.

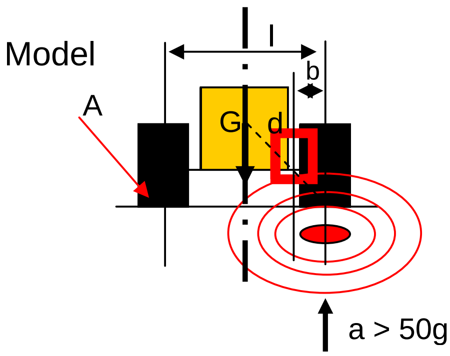


Fig.5.12. Model of tractor unit for calculating forces acting on breakable connection holes.

In normal working load conditions, forces acting on the breakable connection are due to the weight of the powertiller (mg) and to the torque applied to each wheel by the engine (T_w).

Therefore, forces acting on breakable connections holes are as reported in fig.5.13.

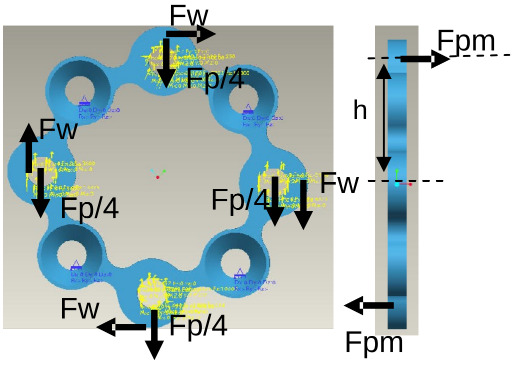
	$F_p = \frac{1}{2} mg = 1250N$	(5.5)
	$F_{pm} = \frac{F_p \cdot b}{2 \cdot h} = \frac{1250 \cdot 60}{2 \cdot 47} = 798N$	(5.6)
	$F_w = \frac{T_w}{4 \cdot h} = \frac{2500 \cdot 10^3}{4 \cdot 47} = 13298N$	(5.7)

Fig.5.13. Working load.

Where, F_p is the vertical force acting on the each of the two connections due to powertiller weight; Fpm is the force acting on the connection, perpendicularly to its front side, due to the momentum caused by F_p multiplied by b, the distance between the line of application of F_p, along the middle plane of the wheel and the breakable connection (see fig.5.12); F_w is the force acting on the connection due to the torque applied to each wheel by the engine.

The result of the FEM analysis under working load is shown in fig. 5.14. The maximum principal stress induced on the bridges between holes, designed to weak the structure, is 90MPa; the value of 200MPa doesn't have to be taken into account as it has been obtained along the line where I constrained the connection on cone shaped holes. For cast iron ASTM30 the ultimate tensile strength is S_{ut}= 213.59MPa. Therefore, the connection has a factor of safety of approximately 2.

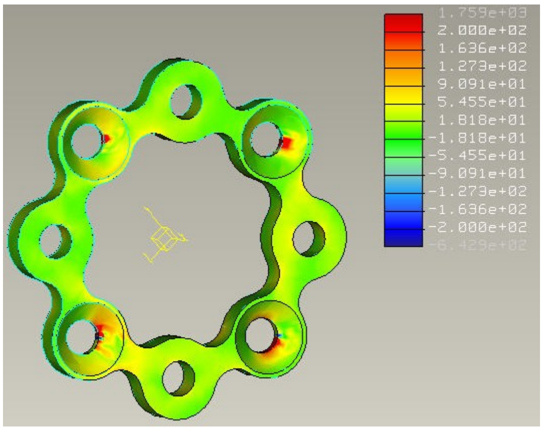


Fig.5.14. FEM analysis result: maximum principal stress induced by working load.

When explosion occurs under the wheel, forces acting on the breakable connection are due to the force generated by the explosion (F_e) and to the torque applied to each wheel by the engine (T_w).

Therefore, forces acting on breakable connections holes are as reported in fig.5.15.

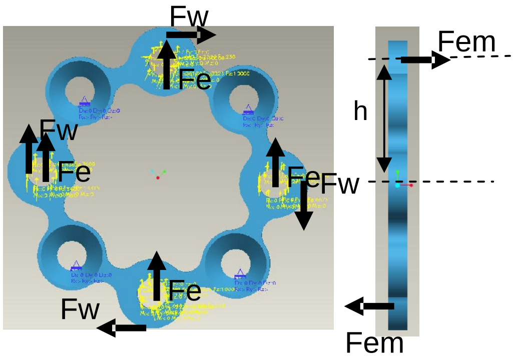
	$F_e = \frac{M_a}{l} = \frac{26375 \cdot 10^3}{648} = 40702N$ $M_a = I_a \cdot \dot{\omega} = (I_G + m \cdot d^2) \cdot \frac{a}{l} =$ $= 36375 \cdot 10^3 N \cdot mm$	(5.8)
	$F_{em} = \frac{F_e \cdot b}{2 \cdot h} = 25980N$	(5.9)
	$F_w = \frac{T_w}{4 \cdot h} = \frac{2500 \cdot 10^3}{4 \cdot 47} = 13298N$	(5.10)

Fig.5.15. Explosion load.

Where, F_e is the vertical force acting on the each of the two connections due to explosion; it is calculated considering the acceleration acting on the axle, due to explosion, to be 50g, the maximum recorded by the accelerometer used in the last test. Acceleration exceeded this value, the maximum the instrument could record, therefore if the connection fails under this force t will fail under real explosion load, which is much higher. F_{em} is the force acting on the connection, perpendicularly to its front side, due to the momentum caused by F_e multiplied by b, the distance between the line of application of F_e, along the middle plane of the wheel and the breakable connection (see fig.5.12); F_w is the force acting on the connection due to the torque applied to each wheel by the engine.

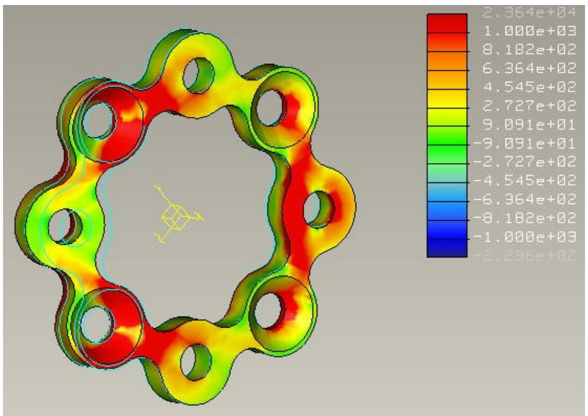


Fig.5.16. FEM analysis result: maximum principal stress induced by explosion load.

The result of the FEM analysis under explosion load is shown in fig. 5.16. The maximum principal stress induced on the bridges between holes, is 1000MPa. For cast iron ASTM30 the ultimate tensile strength is S_{ut}= 213.59MPa. Therefore, the connection would break.

5.3. Second explosion test

In order to verify the suitability of the preliminary version of the tractor unit armoring, based on the concept of the breakable connection, to resist detonation of AP mines, I organized a second blast test in May 2006. It took place another time under the kind supervision of Danilo Coppe, one of the major explosive experts in Italy, in an open air cave near to Fornovo, Parma. Together with Danilo, some of my colleagues of the University of Genova kindly accepted to help me with the test, Matteo Zoppi, Paolo Silingardi, Francesco Orzelli e Wiktor Sieklicki.

Together with the breakable ring, I tested two other breakable connections, simply constituted by two sets of screws, fastening the wheel to the flange, presenting double and single cuts along their body (fig.5.17).

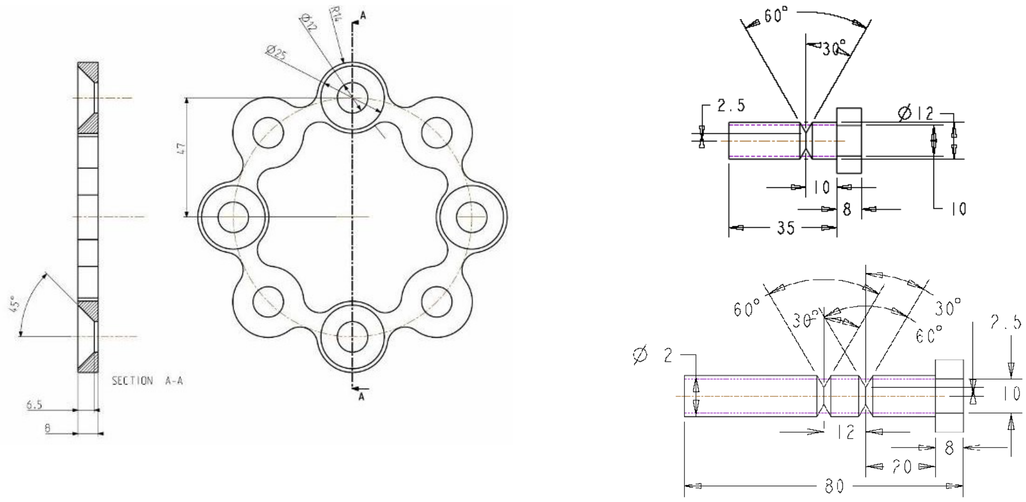
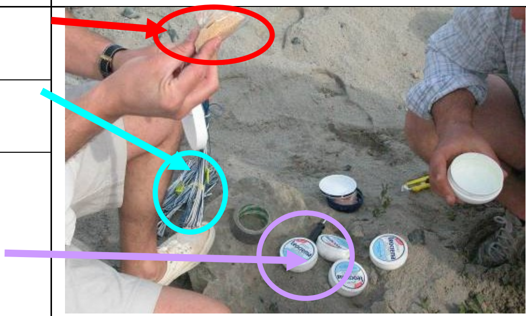


Fig.5.17. Technical drawing of breakable ring and single and double cut screws.

I also had the possibility to test tires filled in with different special elastic gums, kindly provided by GoGomma, who has also agreed to provide a workshop in the field in Sri Lanka with second hand machines necessary to fill in every kind of wheel with those special elastic gums, in case of positive test result. Wheels tested were common agricultural pneumatic wheels, kindly provided by Grillo Spa, filled in with two different types of elastic gums: GoFill tyre filler and GoSeal tyre sealer. Five explosions took place, with landmines respectively underneath:

1. wheel filled in with GoFill
2. wheel connected to the axle with breakable ring
3. wheel connected to the axle with screws with double cut
4. wheel connected to the axle with screws with single cut
5. wheel filled in with GoSeal

Material used for testing is reported in fig. 5.18.

Material type	Picture	Quantity	Scope	Provided by
TNT		55 g bag x 5 bags	explosive for mines	Danilo Coppe
detonators		5	detonators for mines	Danilo Coppe
plastic containers		5	casings for mines	UNIGE
power tiller		1	power tiller to be tested	UNIGE
accelerometer (and cables and laptop)		1	measuring acceleration on the wheel axis and on the handler of the power tiller	UNIGE
video camera		1	documenting events	UNIGE
tyre filled in with GoFill tyre filler		1	wheel to be tested	wheel by Grillo Spa GoFill by GoGomma

tyre filled in with GoSeal tyre sealer		1	wheel to be tested	wheel by Grillo Spa GoSeal by GoGomma
breakable ring with bridges cut		1	breakable connection to be tested	UNIGE
screws with double cut		4	breakable connection to be tested	UNIGE
screws with single cut		4	breakable connection to be tested	UNIGE

Fig.5.18. material used for testing.

Before actual test could take place, we had to prepare “mines”. As proper mine casings were not readily available, I used small plastic screw top containers instead. The containers were approximately the same size as real mines generally found in the Vanni region: P4Mark1 and Type72, 70 mm in diameter and 40 mm high.

“Mines” were prepared by placing the plastic bags containing 55g of TNT inside the casing, after having cut a small hole in the bag to allocate the detonator. Before closing the casing and wrapping around adhesive tape, sand was added to fill the remaining space, approximately 20mm high.

Terrain was wet gray clay; soil surface was sparkled with small stones as it can be seen by the picture in fig.5.20. Weather was hot and dry, temperature around 25°C.

Fig.5.19. Preparation of “mines”.

Fig.5.20. Terrain of test site.

Data from tests was recorded with two sensors: an accelerometer, able to measure accelerations within the range of -500g, +500g, placed on the axle under which explosions took place and a video camera placed approximately 7m away from the power tiller.

Data recorded with the accelerometer, through a laptop containing an acquisition card connected to the accelerometer through a long cable, was not synchronized with the triggering of the explosive charge or with data recorded by the camera, as it was impossible to actuate all systems exactly at the same time manually.

Results [5.4] from tests were unexpected; although working at absorbing some of the energy transported by the shock wave, breakable connections are not suitable to protect the power tiller from damages caused by the detonation of AP landmines under wheels.

In fact, although the wheel connected through the breakable connection dropped off during two of the three explosions, the physical detachment happened after the blast wave was already passed through the connection and entered the power tiller structure, as it can be seen from measures recorded by the accelerometer placed on the axle (fig.5.21). This means that the blast wave traveling at supersonic speed passed through the medium before it had the time to deform and break. The breakable connection worked at reducing the total energy transmitted by the blast wave to the power tiller, but by filtering only waves at high frequency. Therefore, the breakable connection designed did not prevent low frequency waves, responsible for dangerous mechanical vibrations to enter the powertiller drive train, acting more like a high frequency filter than a low frequency filter, as expected.

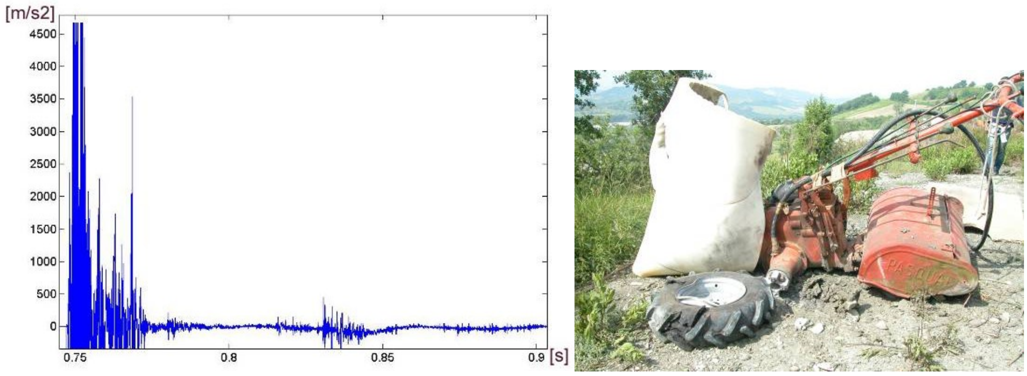


Fig.5.21. Test n°4: zoom on the acceleration [m/s2] versus time [s] during time between 0,747s (when explosion started) and 0,9s (when the event ended); power tiller after explosion.

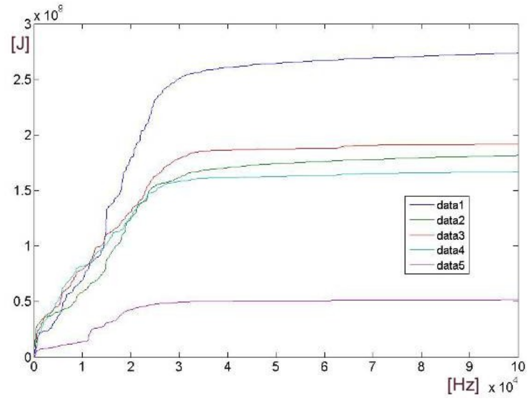


Fig.5.22. Energy[J] versus frequency[Hz] passing through the power tiller in the five explosions (data1 refers to first explosion, data5 to the fifth).

The wheel rims got damaged almost in the same manner after each explosion except for the second, when the mine was not placed directly underneath but slightly internally. Therefore, no advantages of using the breakable connection are visible on wheel deformations. The reason for this could be that they remain physically connected to the power tiller until the breakable connection breaks, absorbing the same low frequency waves of the blast wave that pass through the power tiller structure.

While the wheel filled in with GoFill could keep on working after the fourth explosion, although partially damaged, the wheel filled in with GoSeal could definitely not keep on working after the first explosion.

The energy released by the blast wave and passed through the power tiller during the fifth explosion was 5 times less than the energy passing through the structure during the first explosion and 3 times less than the energy passing through the structure when the breakable connection was in place (fig.5.22) [5.5]. This suggests that pneumatic wheels filled in with air and

liquid, in this case GoSealer, work at reducing the total energy transmitted to the structure better than solid wheels, filled in with GoFill. This result is in accordance with results obtained by Defence R&D Canada [5.6] who conclude that detonations under water-filled tires transferred more kinetic energy upwards than either the standard or runflat tires.
Detailed analyses of results of each explosion and the pre-test are reported hereafter.

5.3.1. Pre-test

In order to have a more definitive result from the test in the field I have decided to pre-test the breakable ring specifically designed for connecting the wheel to the power tiller axle in the laboratory of the university before going to the field in the cave near to Fornovo, Parma. Upon the results of the tests I would have looked for other solutions to be tested in the field together with the breakable ring opportunely modified if required.
The breakable ring was designed and dimensioned to be built of cast iron 30 ASTM grade. This material was chosen for its characteristics of brittle fracture. Unfortunately the material was not available to the workshop and is generally not easy to find; so I have decided to build it with aluminium alloy 2011 T6, which is easier available and presents similar characteristics.
The pre-test could take place only thanks to the kind assistance of prof. Costantino Balboni and Maurizio Gandoglia of the University of Genova.
The functional material used during the pre-test is reported in fig.5.18.

Material type	Picture	Quantity	Scope	Provided by
testing machine		1	apply increasing load on the piece to be tested	UNIGE
breakable ring		1	piece to be tested	UNIGE

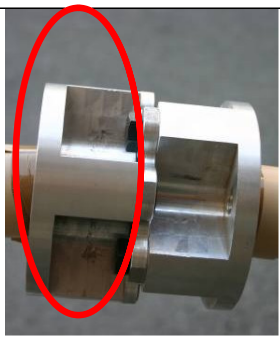
flange		2	holding the breakable connection in place during test, offering a surface on which applying force and therefore momentum on the piece	UNIGE
support		1	supporting the breakable connection during test	UNIGE

Fig.5.18. Material used in pre-test.

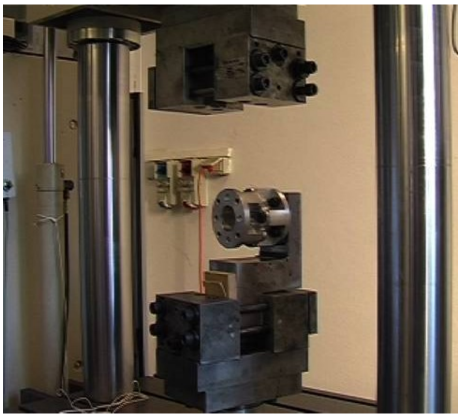


Fig.5.19. Picture of the testing machine and support, flanges and breakable ring assembled together.

The test was conducted applying a constantly increasing load on the top of the flange supporting the breakable ring. The machine gave the displacement of the same end effector applying the force, as output. The force was applied at a distance of 40mm from the breakable ring. From the graph plotted by the machine (fig.5.20), the behaviour of the ring can be analysed.

The ring broke when the load applied reached 48.000N. At this stage 2 bridges of the ring structure collapsed and the 6 others deformed plastically. The corresponding displacement downwards from the original position, of the end-effector applying the force, was 5mm.

When the displacement of the end effector applying the force on the flange started increasing again and the end-effector begun exerting force on the flange again, a second collapse occurred at 38.000N; the corresponding displacement from the original position was 7.5 mm. At this stage, other 2 bridges of the breakable ring collapsed and I stopped the test.

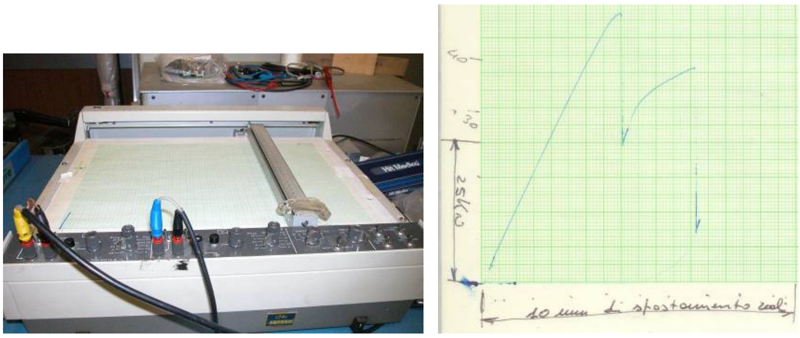


Fig 5. Plotting machine and plot

During the application of the force sharp noises were heard, the first at 15.000N. Visible deformation started around 20.000N.

Pictures of the breakable ring broken after the pre-test are shown in fig.5.21. The system is still placed into the testing machine. The end-effector applying the force is highlighted with a red arrow.

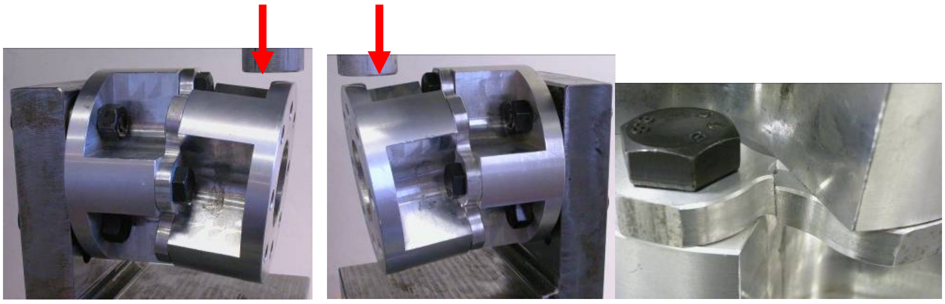


Fig.5.21. Breakable ring after the pre test: front and rear and particular of a broken bridge.

Conclusions drawn from the pre-test were useful for better preparing the test in the field. Unfortunately, the ring did not break as we expected. Collapsing of the bridges happened only when the force applied was 48.000N, higher than the force due to explosion, which I estimated equal to 41.000N, from the previous test.

Although this can not represent a problem as load applied to the breakable connection during the pre-test was static while during explosion the load is dynamic, the ring did not behave as predicted, having not caused flanges to detach. In fact, the material was not as brittle as I thought, presenting also plastic deformations: these can be seen from the pictures reported in fig.5.22.

Fig.5.22. Plastic deformations of the breakable ring after the pre-test.

Due to plastic deformation, flanges did not disconnected completely from each other; this is not desirable as the role of the breakable ring is to stop the shock wave transmission and this can happen only if physical connection is interrupted.

Therefore I thought about testing other breakable connections between the wheel and the axle. I used a set of simple screws cut in two different places, favouring brittle fracture in those places, and a set of screws cut in only one place (fig.5.23).

Fig.5.23. Screws with double and single cut to be tested as alternative breakable connection.

After the pre-test I decided to make more fragile the bridges of the ring in order to facilitate their fracture against the plastic deformation. I made a cut approximately 1mm deep into all the 8 bridges of the ring (fig. 5.24).

Fig.5.24. Breakable ring with all bridges cut, to be tested.

5.3.2. Test n°1: landmine under wheel filled in with GoFill

Aim

The aim of the first test was to see the effects of an explosion on the tyre filled in with GoFill tyre filler and on the rim connected rigidly through the flange to the power tiller axle.

I measured the acceleration on the wheel axis and observed the effects on the chassis and on the wheel after the explosion of the mine underneath. I was looking for tire and rim deformations caused by the explosion.

Test bed

The test bed has been prepared burying the “mine” right under soil surface. A little hoe has been used to lift the soil in order to create the space necessary to allocate the “mine”.

Fig.5.25. Mine placement for the first test and position of the accelerometer.

I considered this to be the worst case. In fact, while in the Vanni region in Sri Lanka mines are found buried up to 100mm deep, the worst blast effect happens when mines are near to the soil surface. When they are buried deeper, once activated their blast wave travels through the soil and looses power on its way.

A hoe similar to the one we used, is the tool generally employed to bury real mines. When they are buried they are generally near to the surface; after years they can move deeper because of soil movements, floods or other weather conditions which have occurred with time.

After burying a “mine” right under soil surface, as in the previous test; we placed the wheel filled in with GoFill of the power tiller right over it. The accelerometer was placed on the wheel axis as near as possible to the wheel standing over the “mine” in order to measure forces on the tiller’s axis.

In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed foam rubber 50mm thick between the wheels and the engine. A camera, protected by a pallet, placed 7m away from the place of explosion has been used to record the whole dynamic of explosion.

Fig.5.26. Camera recording the event.

Results

Explosion raised the wheel over the landmine of about 300mm. The crater made by the explosion was approximately 450mm in diameter and 100mm deep. The wheel was not damaged too much. The external part of the rim right over the mine bended slightly as shown in fig.5.27.

Fig.5.27. Wheel filled in with GoFill after first explosion, seen from the side, after 180° rotation and from the top.

The tire got damaged but no ribs were lost and the external shape was kept, allowing it to be used further if necessary. The external part of the tyre opened but the tube remained intact, as shown in fig.5.27.

Internally, toward the chassis, the rim got slightly more damaged than externally, as shown in fig.5.28. The picture shows also a deformation of the tyre on the sidewall area, that got compressed.

Fig.5.28. Wheel filled in with GoFill after first explosion, seen from the internal side, after 180° rotation.

The chassis as already observed in previous test, was not damaged by the explosion.

The accelerometer placed on the wheel axis, although able to measure accelerations in the range -500g / +500g, much wider than the one employed in the previous test (-50g /+50g), carried out in November 2005, was not able to record the maximum acceleration occurred during explosion.

Luckily, acceleration of the power tiller axis exceeded 500g only for 0,004s after the explosion started; all other values of acceleration are lower.

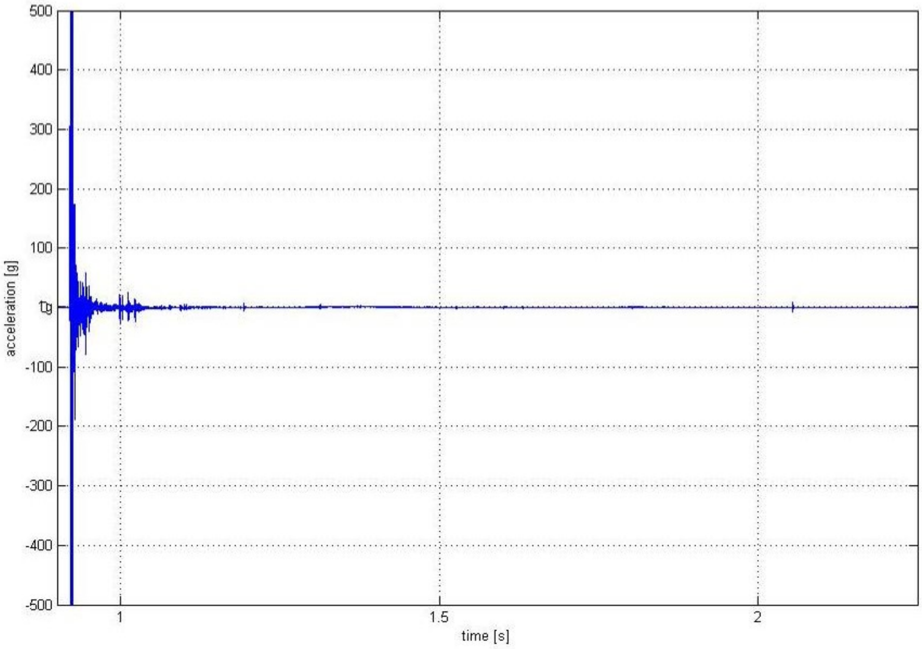


Fig.5.29. Acceleration versus time during the whole explosion n°1 process.

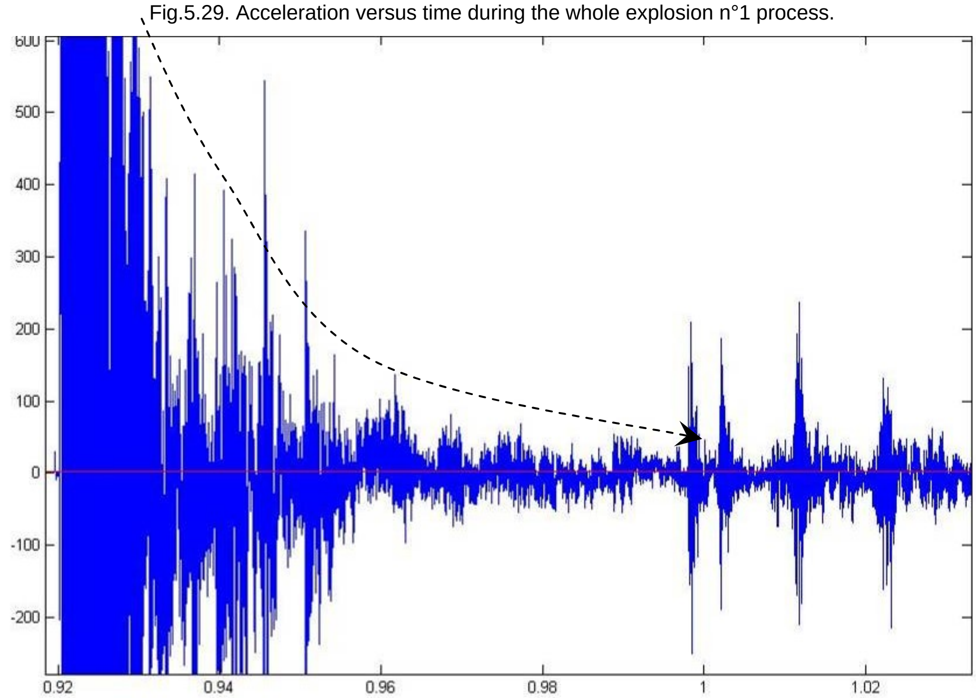


Fig5.30. Zoom on the acceleration versus time during time between 0,92 and 1.034s.

The explosion event started when detonation occurred, at t = 0,9195s after measurement started. The explosion itself occurred at t = 0,92s. From fig.5.29 the acceleration on the wheel axis due to the detonation of the charge can be distinguished from the acceleration due to the explosion itself. The short vertical line occurring at 0,9195s, is the acceleration due to detonation. It reached the maximum value of 3g. The next vertical line occurring at 0,92s, is the first acceleration recorded due to the explosion. Acceleration recorded is oscillatory as the power tiller structure reacts vibrating to the blast wave impulse.

As soon as the explosion started, acceleration begun increasing very rapidly, almost instantaneously, growing up over 500g at 0,9205s.

After 0,004s, at time t = 0,9245s, acceleration started decreasing in amplitude approximately constantly until t = 0,998s, when it went to zero. Therefore acceleration decreased for 0,0735s.

An exception in the decreasing behaviour of the acceleration amplitude was an increment in acceleration at t = 0,9456, when the acceleration reached 544,6m/s^2.

Other four relevant increments in acceleration amplitude occurred after: 209,6 m/s^2 at time = 0,9984s, 186,9 m/s^2 at time = 1,002s, 237 m/s^2 at time = 1,012s and 132,2m/ s^2 at time = 1,022s.

From the graph in fig.5.32, reporting frames taken from the video recorded by the camera and values of acceleration versus time, it can be seen that the power tiller reached the maximum vertical displacement around 0.24s after the explosion started: therefore, at t = 1.16 in the acceleration graph. Therefore, those increments in acceleration after the beginning of the explosion, respectively 0,0256s, 0,0307s, 0,0784s, 0,082s and 0,092s were possibly due to the impact with the accelerometer of different objects of the soil surface ejected at very high speed against the power tiller chassis by the blast wave.

From the graph in fig.5.31, of vertical displacement versus time, obtained by integrating twice the acceleration curve, it can be verified that the power tiller kept on moving upwards for approximately 0,24s after explosion occurred. I obtained the graph in fig.5.31 by integrating twice the function of the acceleration versus time between t = 0,9425s, when the acceleration started decreasing below 500g, re-entering the sensor range and t = 1,48s, when from frames extrapolated from the video it can be seen that the power tiller goes back to ground level. I cut the function of acceleration versus time before integration because values of acceleration over 500g have not been registered by the sensor. I have used a filtering function within the integrating function to eliminate the noise registered by the sensor: this function constraints the displacement to be zero at both extremes of integration. The dashed line can be considered representing approximately the zero on the y axis. As, when acceleration decreases below 500g, when vertical displacement starts to be shown on the graph, the power tiller has already started moving upwards. Therefore, mainly qualitative results can be obtained from the graph: the power tiller kept on moving upwards for 0.121s after explosion started (+/- 0.08s resolution of the camera). Then, started moving downwards until t = 1.369s, 0.449s (+/- 0.08s resolution of the camera) after the explosion started, below ground level, the dashed line on the graph, because of the crater made by the explosion under the wheel. The next relevant increment in acceleration amplitude occurred at t = 2,0545s, 1,1345s after the explosion started, and it was 8,789g.

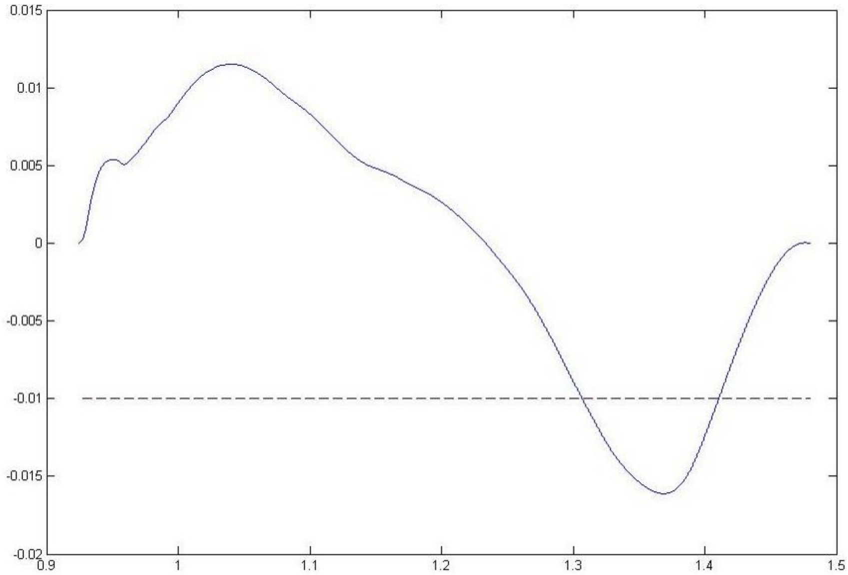
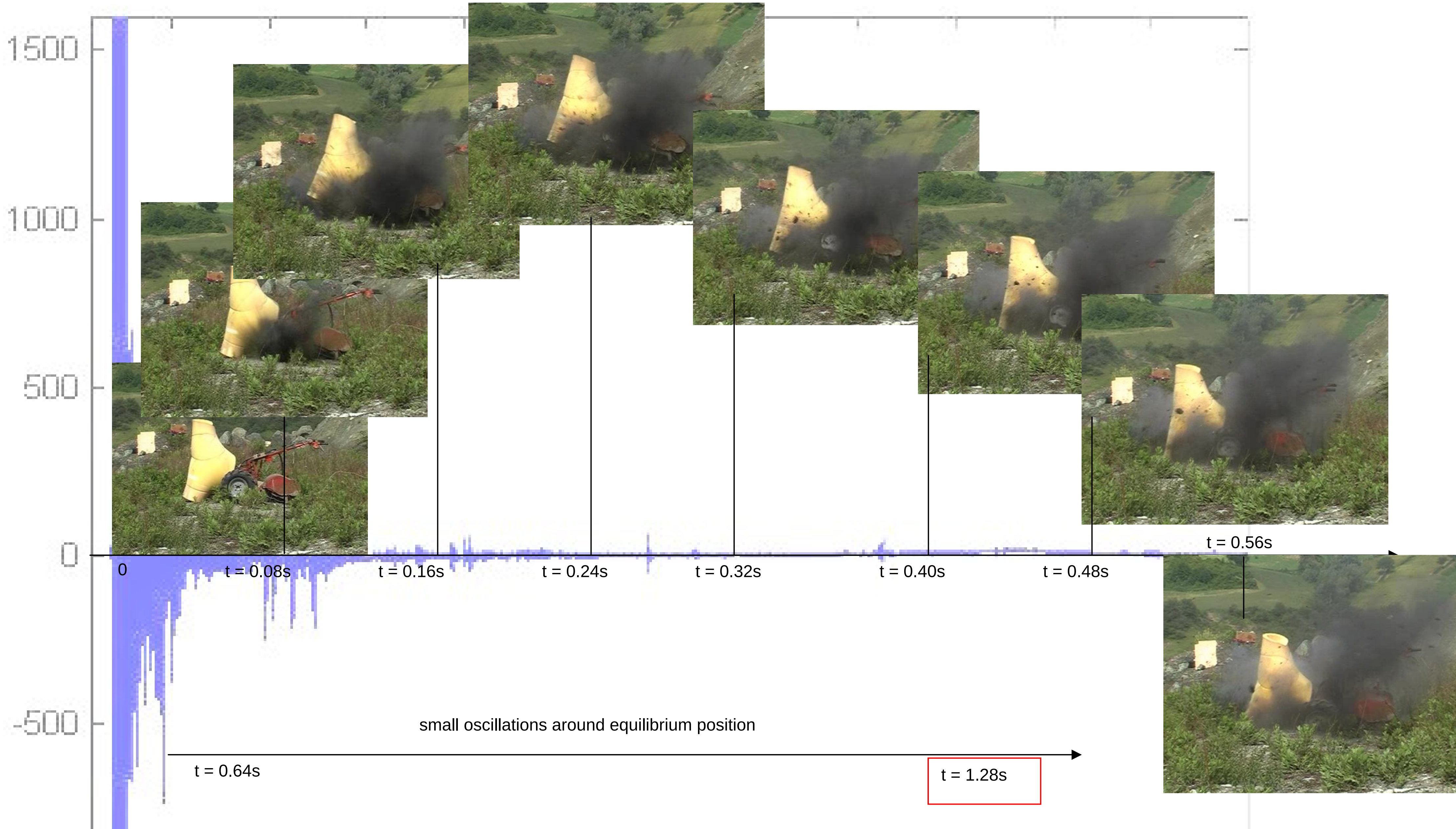


Fig.5.31. Displacement[m] versus time during time between 0,92 and 1,48s.

From the graph reporting frames taken from the video recorded by the camera and values of acceleration versus time, it can be seen that between t = 0,64s and t = 1,28s after explosion started, the power tiller oscillated around equilibrium position; the last increment in acceleration amplitude can therefore be due to one of the impact with ground that made the power tiller oscillating.

From frames extrapolated from the video taken during the first explosion, I found out that around 1s after explosion started the power tiller went back in the original position; therefore this last increment in acceleration can be due to the impact of the power tiller with ground.


1500
1000
500
0
-500
0
t = 0.08s
t = 0.16s
t = 0.24s
t = 0.32s
t = 0.40s
t = 0.48s
t = 0.56s
small oscillations around equilibrium position
t = 0.64s
t = 1.28s

5.3.3. Test n°2: landmine under wheel connected to the axle with breakable ring

Aim

The aim of the second test was to verify if the breakable ring with cut bridges broke due to the explosion, if it worked at reducing the acceleration transmitted to the axle and if it caused the wheel to drop off. At the same time I also wanted to see how much the tyre filled in with GoFill was damaged when the wheel was connected through the breakable ring.

I measured the acceleration on the wheel axis and observed the effects on the chassis and on the wheel after the explosion of the mine underneath.

Test bed

Before burying a “mine” right under soil surface, I unscrewed the wheel filled in with GoFill from the flange to place the breakable ring in position and I screwed it in place again.

Fig.5.33. Breakable ring in position for the second test.

After burying the mine as in previous test, we place the wheel filled in with GoFill and connected with the breakable ring to the power tiller over it. We rotated the wheel in order to have the part damaged by the first test approximately 45° away in anti-clockwise direction.

Fig.5.34. Wheel filled in with GoFill in position for the second test and mine placement.

Differently from previous tests, I placed the wheel (140mm width) approximately 40mm away from the mine, externally. This was meant to help the breakable ring to break thanks to the momentum caused by the explosion, as I have designed the ring to break easier when a bending moment is applied on it.

The accelerometer was placed on the wheel axis in the same place of the previous test. In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed foam rubber 50mm thick between the wheels and the engine. A camera, protected by a pallet, placed 7m away from the place of explosion has been used to record the whole dynamics of explosion.

Results

Explosion raised the wheel over the landmine of about 200mm. The crater made by the explosion was approximately 350mm in diameter and 130mm deep. The wheel did not drop off but stayed in place, although the breakable ring broke.

Fig5.35. Power tiller during and after second test.

The wheel was damaged less than in the previous test. The rim was not damaged further, the only visible deformation was the one caused by the first explosion, both on the external and on the internal side. The tire got damaged but no ribs were lost and the external shape was kept, allowing it to be used further if necessary. The external part of the tire opened but the tube remained intact, as shown in fig.5.36. This time, also the sidewall got slightly damaged.

Probably the wheel was less damaged than in the previous test because it was placed 40mm aside from the mine rather than right over it.

Fig.5.36. Tyre after second test, seen form the top, after 180° rotation.

Four bridges of the breakable ring broke, as it is shown in the picture in fig.5.37, taken after having unscrewed the wheel.

The accelerometer placed on the wheel axis, although able to measure accelerations in the range -500g / +500g, was not able to record the maximum acceleration occurred during explosion. Luckily, acceleration of the power tiller axis exceeded 500g only within the first 0,0028s after the explosion started; all values of acceleration recorded after are lower.

Fig.5.37. Breakable ring after second test

From fig.5.38 it can be seen that the explosion event started when detonation occurred, at t = 0,7736s after measurement started. The explosion itself occurred at t = 0,7739s.

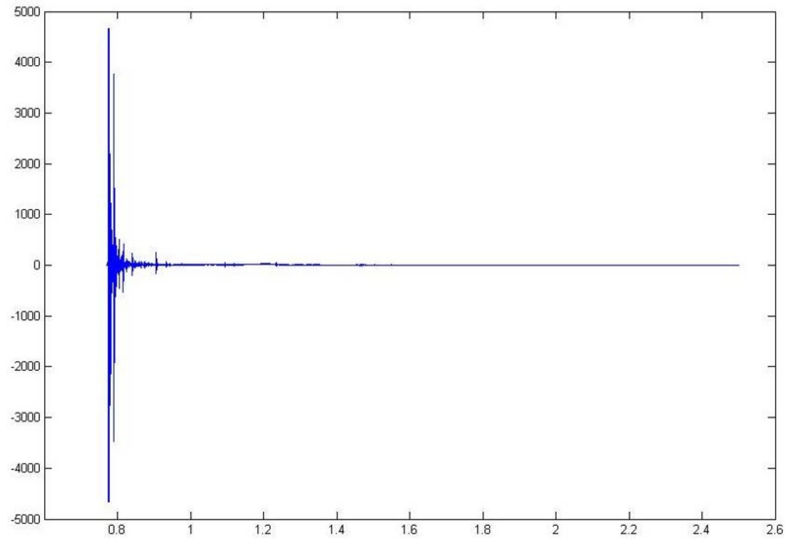


Fig.5.38. Acceleration [m/s^2] versus time [s] during the whole explosion n°2 .

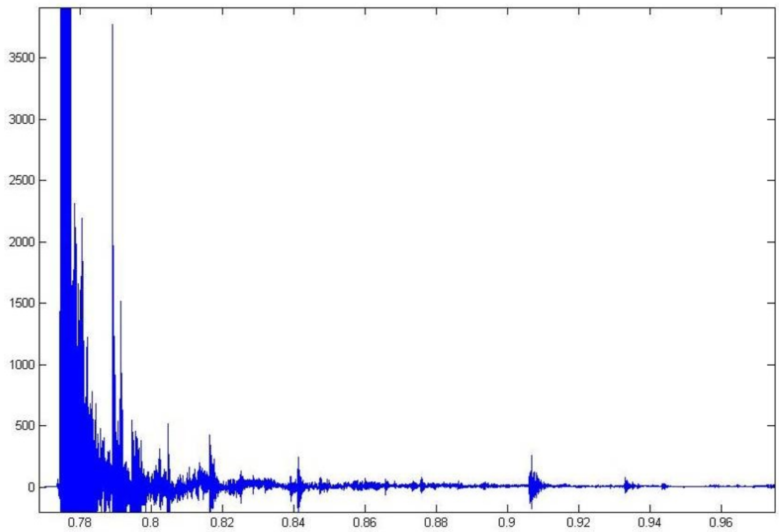


Fig5.39. Zoom on the acceleration versus time during time between 0,77 and 0.97s.

From fig.5.38 the acceleration on the wheel axis due to the detonation of the charge can be distinguished from the acceleration due to the explosion itself. The short vertical line occurring at 0,7736s, is the acceleration due to detonation. It reached the maximum value of 6g. The next vertical line occurring at 0,7739, is the first acceleration recorded due to the explosion. Acceleration recorded is oscillatory as the power tiller structure reacts vibrating to the blast wave impulse. As soon as the explosion started, acceleration begun increasing very rapidly, almost instantaneously, growing up over 500g at 0,7745s. After 0,0028s, at time t = 0,7773s, acceleration started decreasing in amplitude approximately constantly until t = 0,7889s. Therefore acceleration decreased for 0,0116s.

Subsequently, acceleration started increasing in amplitude again reaching 3774 m/s^2 at t = 0,7891s, 0,0152s after explosion started. This could be the time at which the breakable connection broke, maybe having reached its resonance frequency. Under sinusoidal excitation, the response of a system becomes increasingly large if the excitation frequency is close to one of the natural frequencies of the system: this phenomenon is called resonance. The frequency at which this very high acceleration occurred can be extrapolated from the graph of power spectrum density of acceleration versus frequency.

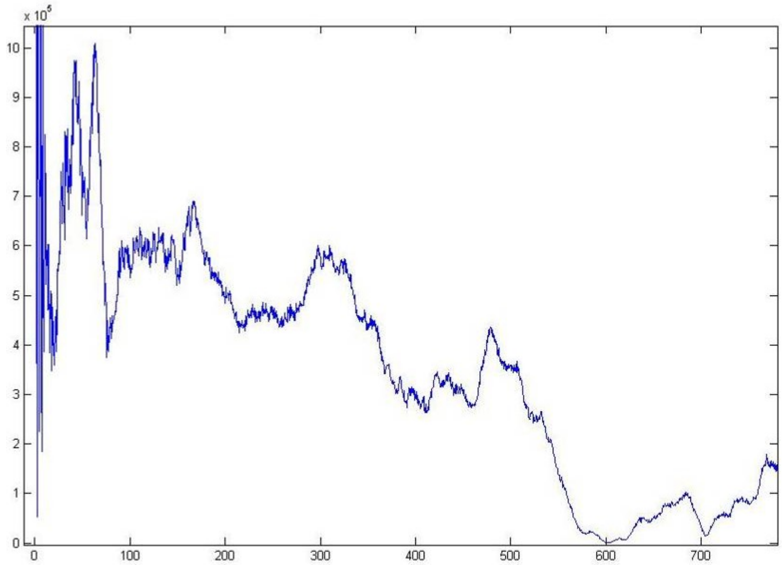


Fig.5.39. Zoom on the power density spectrum [(m^2/s^4)/Hz] versus frequency [Hz] between 0 and 800 Hz.

The highest power density of the signal, in the range of frequencies between 1 and 1000Hz characteristic of mechanical vibrations, occurred around 60Hz and reached the value of 10^{6}(m^2/s^4)/Hz. This frequency could be one of the natural frequencies of the breakable connection. After t = 0,7891s, acceleration started decreasing in amplitude again; the following moderate increments in acceleration amplitude, can be due to the impact with the accelerometer of different objects of the soil surface ejected at very high speed against the power tiller chassis by the blast wave, as in the previous test.

The chassis as already observed in previous test, was not damaged by the explosion.

The analysis of the effects of the breakable connection at reducing damages caused by the explosion on the chassis and sensible parts can be done only comparing results obtained with the accelerometer in different explosions.

5.3.4. Test n°3: landmine under wheel connected to the axle with screws with double cut

Aim

The Aim of the third test was to verify if the breakable connection made with screws with double cut broke due to the explosion, if it worked at reducing the acceleration transmitted to the axle and if it caused the wheel to drop off. At the same time I also wanted to see how much the tire filled in with GoFill was damaged when the wheel was connected through this breakable connection. I measured the acceleration on the wheel axis and observed the effects on the chassis and on the wheel after the explosion of the mine underneath.

Test bed

Before burying a “mine” right under soil surface, I screwed the wheel filled in with GoFill to the flange using the screws with double cut.

Fig.5.40. Screws with double cut in position for the third test.

After burying the mine as in previous test, we placed the wheel filled in with GoFill and connected with the screws to the power tiller over it. We rotated the wheel in order to have the part damaged by previous explosions away from over the mine. The accelerometer was placed on the wheel axis in the same place of the previous test. In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed foam rubber 50mm thick between the wheels and the engine. A camera, protected by a pallet, placed 7m away from the place of explosion has been used to record the whole dynamic of explosion.

Results

The crater made by the explosion was approximately 300mm in diameter and 100mm deep. The wheel dropped off and the screws broke. The wheel was found 400mm away from the flange.

Fig5.41. Power tiller after third test.

The wheel was damaged. The rim bended both on the external and on the internal side. The tire got damaged but no ribs were lost and the external shape was kept, allowing it to be used further if necessary. The external part of the tire opened but the tube remained intact, as shown in fig.5.42. This time, also the sidewall got slightly damaged.

Fig.5.42. Tire after third test, dropped off on the ground.

All four screws broke, but in a slightly different way as it can be seen from Fig5.43.

Fig.5.43. Screws with double cut broken after third test.

The accelerometer placed on the wheel axis, although able to measure accelerations in the range -500g / +500g, was not able to record the maximum acceleration occurred during explosion. Luckily, acceleration of the power tiller axis exceeded 500g only two times after the explosion started; all the other values of acceleration recorded are lower.

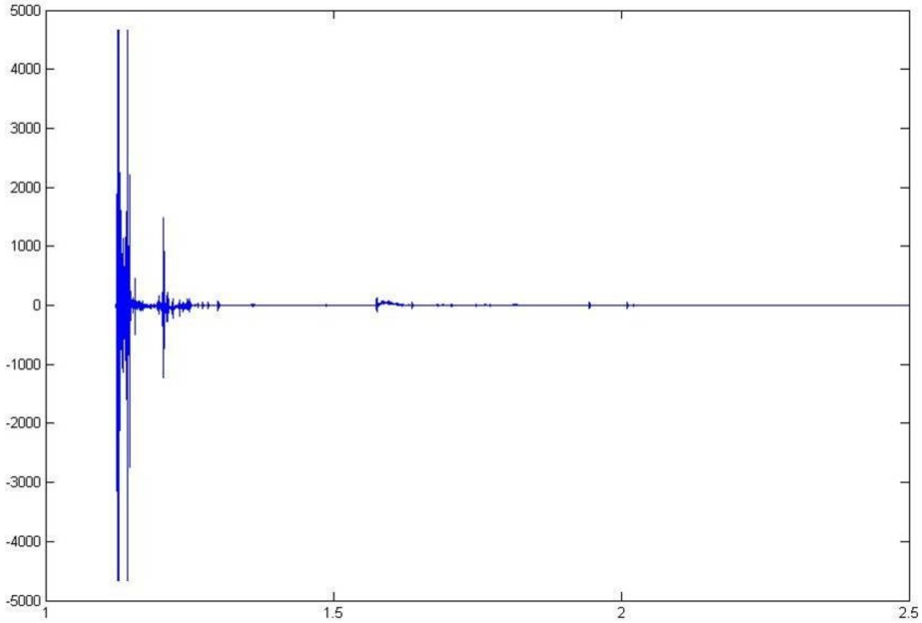


Fig.5.44. Acceleration [m/s^2] versus time [s] during the whole explosion n°3 .

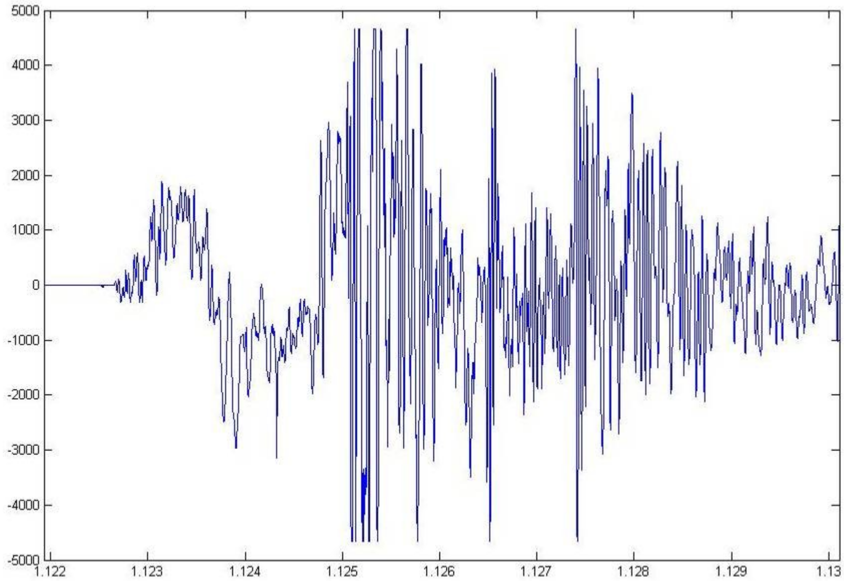


Fig.5.45. Zoom on the acceleration [m/s^2] versus time [s] during time between 1,122 and 1,13s.

The explosion event started at t = 1,1225s after measurement started. The acceleration due to detonation can not be recognised from the graph. From fig.5.45 the initial behaviour of acceleration versus time can be analysed. Between t = 1,1225s and t = 1,1245s acceleration oscillated along a sine curve reaching the maximum value of 1880 m/s^2 at t = 1,123s and the minimum value of -3149 m/s^2 at t = 1,124s.

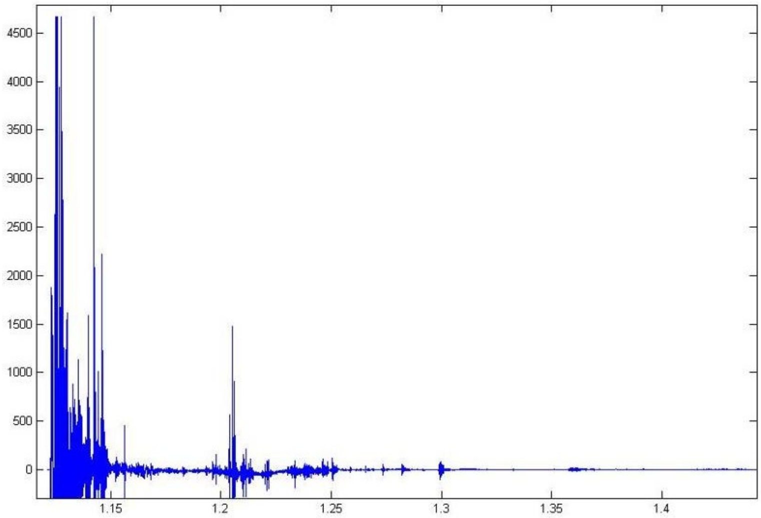


Fig.5.56. Zoom on the acceleration [m/s^2] versus time [s] during time between 1,122 and 1,45s.

Later on the acceleration started oscillating along the horizontal straight line at $0 m/s^2$, increasing very rapidly over 5000 m/s^2 at t = 1,1251s. After 0,0023s, at time t = 1,1274s, acceleration started decreasing in amplitude approximately constantly until t = 1,1421s. Therefore acceleration decreased for 0,0147s. Subsequently, acceleration started increasing in amplitude again exceeding 5000m/s^2 at t = 1,1422s, 0,0197s after explosion started.

This could be the time at which the breakable connection broke, maybe having reached its resonance frequency. The frequency at which this very high acceleration occurred can be extrapolated from the graph of power spectrum density of acceleration versus frequency.

The highest power density of the signal, in the range of frequencies between 1 and 1000Hz characteristic of mechanical vibrations, occurred around 400Hz and reached the value of 1,2*10^^{6}(m^2/s^4)/Hz. This frequency could be one of the natural frequencies of the breakable connection.

After t = 1,1422s, acceleration started decreasing in amplitude again; the following moderate increments in acceleration amplitude, can be due to the impact with the accelerometer of different objects of the soil surface ejected at very high speed against the power tiller chassis by the blast wave, as in the previous test.

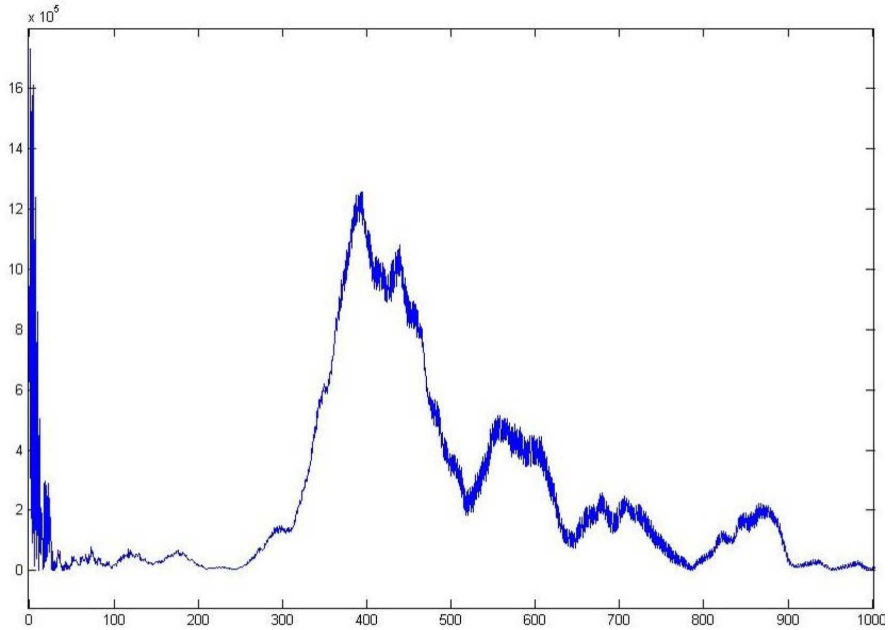


Fig.5.57. Zoom on the power density spectrum [(m^2/s^4)/Hz] versus frequency [Hz] between 0 and 900 Hz.

The chassis as already observed in previous test, was not damaged by the explosion.

The analysis of the effects of the breakable connection at reducing damages caused by the explosion on the chassis and sensible parts can be done only comparing results obtained with the accelerometer in different explosions.

5.3.5. Test n°4: landmine under wheel connected to the axle with screws with single cut

Aim

The Aim of the fourth test was to verify if the breakable connection made with screws with single cut broke due to the explosion, if it worked at reducing the acceleration transmitted to the axle and if it caused the wheel to drop off. At the same time I also wanted to see how much the tyre filled in with GoFill was damaged when the wheel was connected through this breakable connection. I measured the acceleration on the wheel axis and observed the effects on the chassis and on the wheel after the explosion of the mine underneath.

Test bed

Before burying a “mine” right under soil surface, we screwed the wheel filled in with GoFill to the flange using the screws with single cut. During screwing, one screw broke and it was replaced with a new screw with single cut.

Fig.5.58. Screws with single cut in position for the fourth test.

After burying the mine as in previous test, we placed the wheel filled in with GoFill and connected with the screws to the power tiller over it. We rotated the wheel in order to have the part damaged by previous explosions away from over the mine. The accelerometer was placed on the wheel axis in the same place of the previous test. In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed foam rubber 50mm thick between the wheels and the engine. A camera, protected by a pallet, placed 7m away from the place of explosion has been used to record the whole dynamic of explosion.

Results

Explosion raised the wheel over the landmine of about 300mm. The crater made by the explosion was approximately 400mm in diameter and 160mm deep. The wheel dropped off and the screws broke. The wheel jumped approximately 800mm high as it can be seen from the picture taken from the video (fig.5.59).

Fig.5.59. Picture of power tiller during fourth test, taken from the video recorded and powertiller after test.

The wheel was damaged. The rim bended both on the external and on the internal side. The tire got damaged but no ribs were lost and the external shape was kept, allowing it to be used further if necessary. The external part of the tire opened but the tube remained intact, as shown in fig.5.60.

Fig.5.60. Tyre after fourth test, dropped off on the ground and screws with single cut broken after forth test.

All four screws broke as it can be seen from fig.5.60.

The accelerometer placed on the wheel axis, although able to measure accelerations in the range -500g / +500g, was not able to record the maximum acceleration occurred during explosion.

Luckily, acceleration of the power tiller axis exceeded 500g only for 0,0032s after the explosion started; all other values of acceleration recorded are lower.

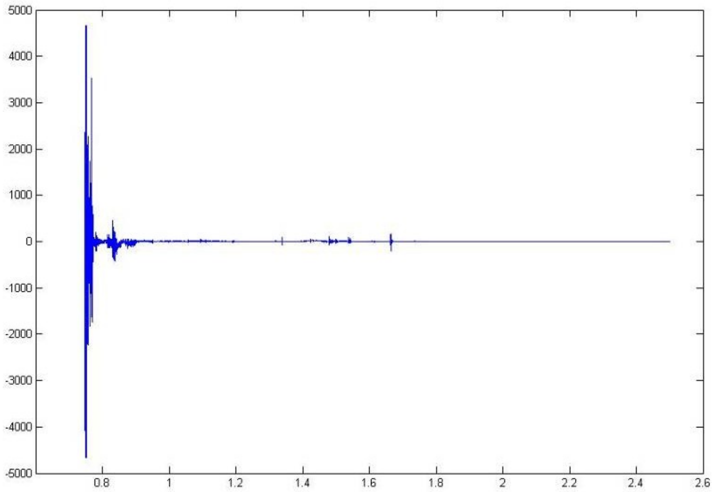


Fig.5.61. Acceleration [m/s^2] versus time [s] during the whole explosion n°4 .

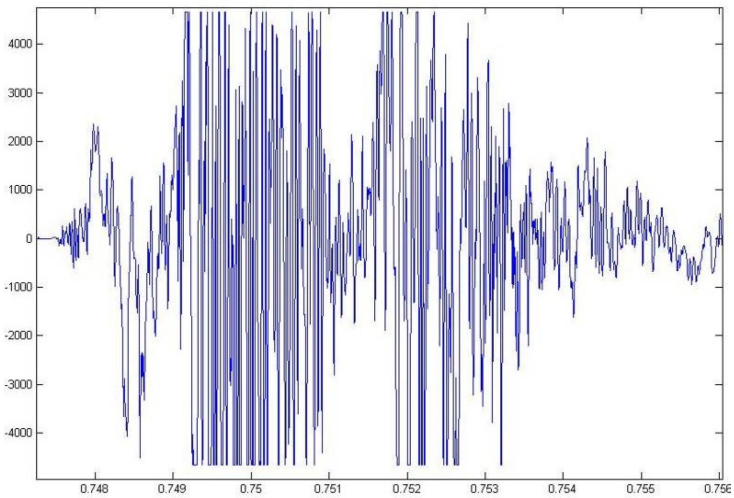


Fig.5.62. Zoom on the acceleration [m/s^2] versus time [s] during time between 0,747 and 0,756s.

The explosion event started at t = 0,7475s after measurement started. The acceleration due to detonation can not be recognised from the graph.

From fig.5.62 the initial behaviour of acceleration versus time can be analysed. Between t = 0,7475s and t = 0,7489s acceleration oscillated along a sine curve reaching the maximum value of 2365 m/s^2 at t = 0,748s and the minimum value of -4510 m/s^2 at t = 0,7486s.

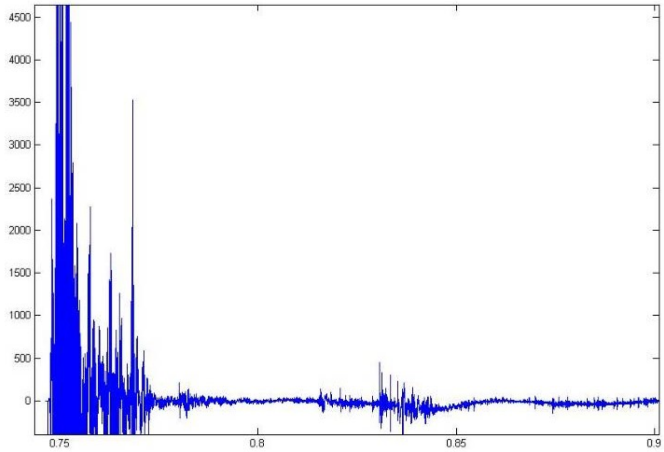


Fig.5.63. Zoom on the acceleration [m/s^2] versus time [s] during time between 0,74 and 0,9s.

Later on the acceleration started oscillating along the horizontal straight line at 0m/s^2, increasing very rapidly over 5000 m/s^2 at t = 0,7492s. After 0,0021s, at time t = 0,7523s, acceleration started decreasing in amplitude approximately constantly until t = 0,7675s. Therefore acceleration decreased for 0,0152s. Subsequently, acceleration started increasing in amplitude again reaching 3528m/s^2 at t = 0,7685s, 0,021s after explosion started.

This could be the time at which the breakable connection broke, maybe having reached its resonance frequency. The frequency at which this very high acceleration occurred can be extrapolated from the graph of power spectrum density of acceleration versus frequency.

The highest power density of the signal, in the range of frequencies between 1 and 1000Hz characteristic of mechanical vibrations, occurred around 740Hz and reached the value of 1,4*10^^{6}(m^2/s^4)/Hz. This frequency could be one of the natural frequencies of the breakable connection.

After t = 0,7685s, acceleration started decreasing in amplitude again; the following moderate increments in acceleration amplitude, can be due to the impact with the accelerometer of different objects of the soil surface ejected at very high speed against the power tiller chassis by the blast wave, as in the previous test.

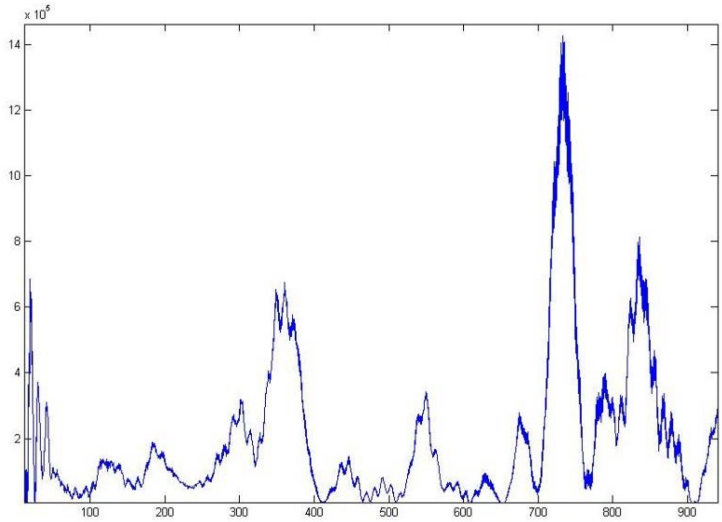


Fig.5.64. Zoom on the power density spectrum [(m^2/s^4)/Hz] versus frequency [Hz] between 0 and 900 Hz.

The chassis, as already observed in previous test, was not damaged by the explosion.

The analysis of the effects of the breakable connection at reducing damages caused by the explosion on the chassis and sensible parts can be done only comparing results obtained with the accelerometer in different explosions.

5.3.6. Test n°5: Landmine under the wheel filled in with GoSeal

Aim

The aim of the first test was to see the effects of an explosion on the tyre filled in with GoSeal, liquid tyre sealant and on the rim connected rigidly through the flange to the power tiller axle.

I measured the acceleration on the wheel axis and observed the effects on the chassis and on the wheel after the explosion of the mine underneath. I was looking for tire and rim deformations caused by the explosion.

Test bed

After burying a “mine” right under soil surface, as in the previous test; we placed the wheel filled in with GoSeal of the power tiller right over it. The accelerometer was placed on the wheel axis in the same place of the previous test. In order to protect the power tiller engine from damages caused by the possible ejection of small stones and soil particles by the blast wave, I placed foam rubber 50mm thick between the wheels and the engine. A camera, protected by a pallet, placed 7m away from the place of explosion has been used to record the whole dynamic of explosion.

Fig.5.65. Placement of the mine for the fifth test.

Results

The crater made by the explosion was approximately 400mm in diameter and 250mm deep.

The wheel was damaged. The rim bended both on the external and on the internal side. The tire got damaged, lost all air inside as well as GoSeal pink liquid. It was impossible to use the wheel further. The external part of the tire opened as well as the tube, as shown in fig.5.66.

Fig.5.66. Power tiller after the fifth test.

The accelerometer placed on the wheel axis, although able to measure accelerations in the range -500g / +500g, was not able to record the maximum acceleration occurred during explosion.

Luckily, acceleration of the power tiller axis exceeded 500g only for 0,0019s after the explosion started; all other values of acceleration recorded are lower.

As shown in fig.5.67, the explosion event started at t = 0,6161s after measurement started. The acceleration due to detonation can not be recognised from the graph. After explosion started, the acceleration started increasing in amplitude very rapidly exceeding 5000 m/s^2 at t = 0,6171s. After 0,0019s, at time t = 0,6171s, acceleration started decreasing in amplitude approximately constantly until t = 0,6405s. Therefore acceleration decreased for 0,0234s.

The following moderate increments in acceleration amplitude, can be due to the impact with the accelerometer of different objects of the soil surface ejected at very high speed against the power tiller chassis by the blast wave, as in the previous test.

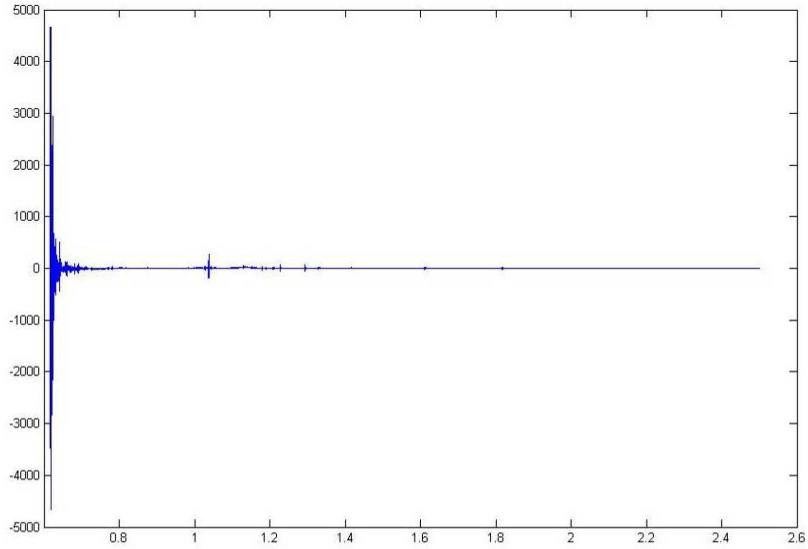


Fig.5.67. Acceleration [m/s^2] versus time [s] during the whole explosion n°5 .

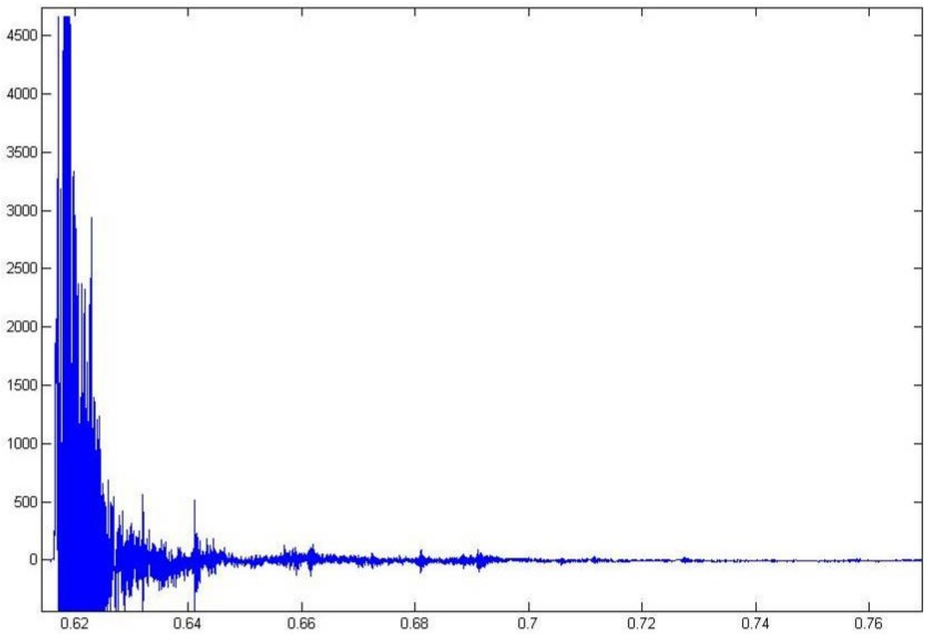


Fig.5.68. Zoom on the acceleration [m/s^2] versus time [s] during time between 0,62 and 0,77s.

The chassis, as already observed in previous test, was not damaged by the explosion.

The analysis of the effects of the breakable connection at reducing damages caused by the explosion on the chassis and sensible parts can be done only comparing results obtained with the accelerometer in different explosions.

5.3.7. Comparison of data obtained with the accelerometer in the five tests

In order to compare data obtained with the accelerometer in different tests it is necessary to manipulate them further. Particularly, it would be interesting to compare the energy associated with the five different explosions: the energy released by the landmine, that passes through the power tiller chassis when different types of breakable connection are in place or when there is none. For each explosion (test), it is possible to plot the density of power spectrum against frequency: a measure of the intensity of the periodic signal with respect to the frequency (fig.5.69). By integrating once the power spectrum density, the energy can be plotted against frequency (fig.5.70). Moreover, as mechanical vibrations are known to reach the maximum frequency of 1.000 Hz, energy transmitted by mechanical vibrations of the power tiller structure can be distinguished from energy transmitted by waves moving into the structure at higher frequencies.

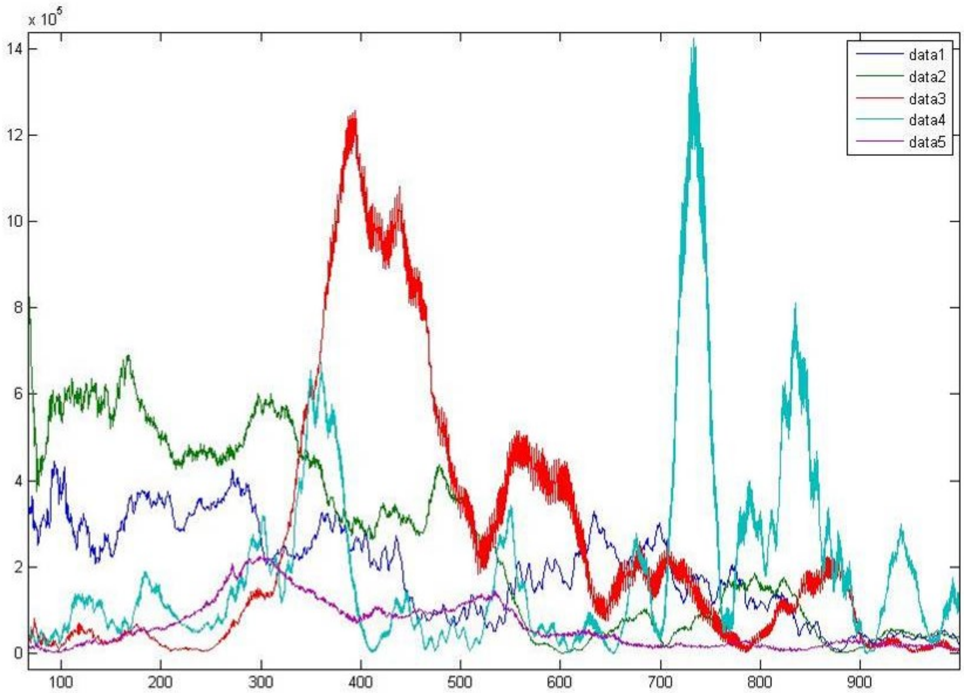


Fig.5.69. Zoom between 0 and 1000 Hz of the power spectrum density versus frequency of the acceleration in the five explosions (data1 refers to first explosion, data5 to the fifth)

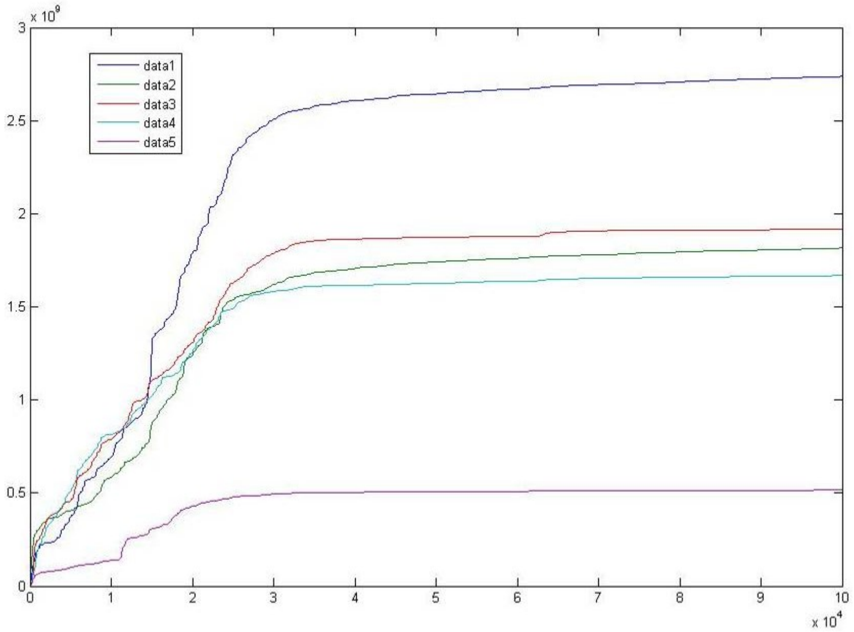


Fig.5.70. Energy[J] versus frequency[Hz] passing through the power tiller in the five explosions (data1 refers to first explosion, data5 to the fifth).

From fig.5.70. it can be seen that breakable connections placed between the wheel and the axle, used in tests 2,3,4 worked at reducing the total energy transmitted to the power tiller, by 1,5 factor with respect to the total energy transmitted in the first explosion when no breakable connection was used.

The minimum energy transferred to the power tiller was registered during the last explosion when no breakable connection was employed and the tyre was filled in with air and GoSeal. This is due to the fact that part of the energy transported by the blast wave was spent in kinetic energy for moving the air and Go Seal out of the tyre that got broken.

The energy transported through the power tiller thanks to mechanical vibrations at low frequencies and thanks to vibrations at higher frequencies can be analysed as well, fig.5.71. From the graphs in fig.5.72, it can be observed that the breakable connections used in tests 2,3,4, while helping reducing the total energy transported through the power tiller, perform better into reducing the energy transported by high frequency vibrations than the energy transported by low frequency mechanical vibrations. This result is unexpected as breakable connections have been designed to stop the blast wave entering the power tiller structure in order not to cause the drive train to vibrate mechanically and therefore got damaged.

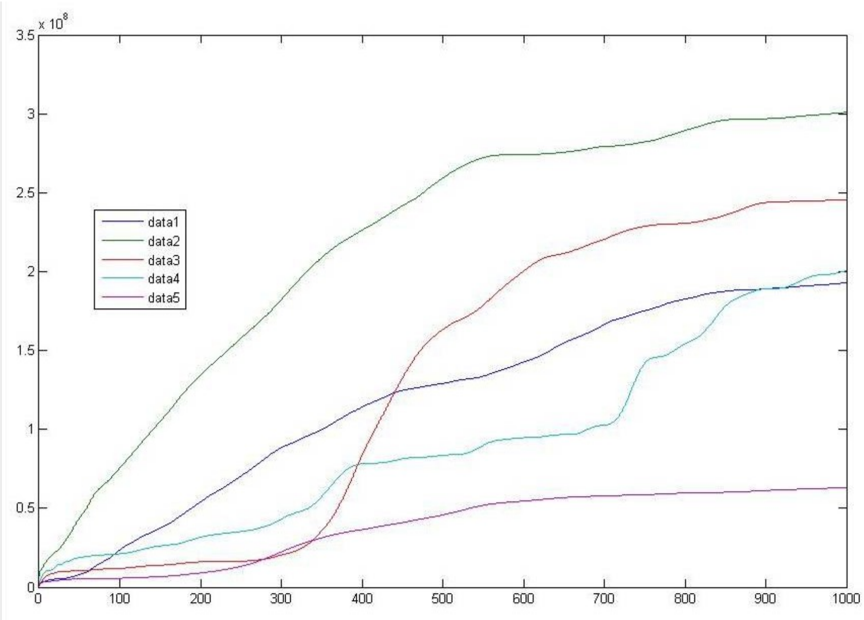


Fig.5.71. Energy[J] versus frequency[Hz] passing through the power tiller in the five explosions (data1 refers to first explosion, data5 to the fifth), transported by mechanical vibrations at low frequencies (1 – 1000 Hz).

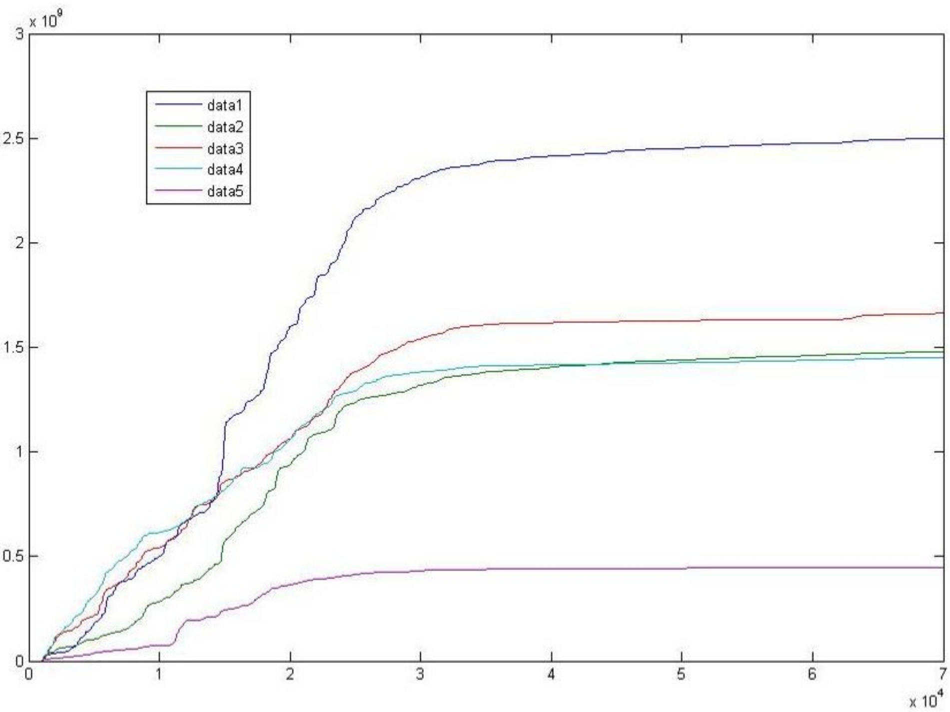


Fig.5.72. Energy[J] versus frequency[Hz] passing through the power tiller in the five explosions (data1 refers to first explosion, data5 to the fifth), transported by vibrations at high frequencies (> 1000 Hz).

5.4. Ideas on tractor unit redesign and preliminary analyses

Upon test results, I decided to place the ground processing tool on the front of the machine. Although it could have been interesting to keep on working on shock absorption devices, to make the tractor unit capable of withstand small landmine blasts, time was getting shorter and I had to concentrate on further steps of the design.

Having the ground processing tool at the front (GP-F working configuration) allows only a light armoring to be used to protect delicate parts of the tractor unit from secondary damages due to explosions possibly induced by the ground processing tool, as landmines should have already been removed when the machine passes. In order to increase traction, I added rubber tracks connecting driven wheels to additional wheels supporting the ground processing tool on the front. Remote control of the tractor unit was then possible by actuating the two semi-axles through brakes, added. Moreover, I believe, but I didn’t have the possibility to test it, that tracks could absorb part of the energy of an accidental explosion underneath by deforming flexibly.

Therefore, when the vegetation cutting tool would be used, the system would work in the configuration shown in Fig.5.73, with both the end-effectors on the front, the vegetation cutting tool supported by the same frame supporting the ground-processing tool.

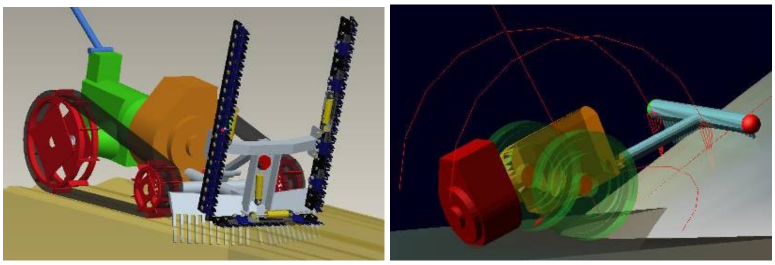


Fig.5.73. Digital mock-up of power tiller with tracks and multi-body model used in preliminary analyses.

Preliminary analyses on the multi body model of the tractor unit modified to support the ground processing tool in the front (fig.5.73) were promising. The tractor unit behaved well at pushing the ground processing tool. To model the soil tool interaction force I used a rough model (eq.5.11) based on visco-elastic force, used in literature [5.7 and 5.8]. Instead of the term proportional to the distance between the tool and the soil, impossible to define in my case, I used a term proportional to the volume of soil moved per time.

$$F = C \cdot v_{t_1} + K' \cdot A \cdot (v_{t_i} - v_{t_{i-1}}) \cdot (t_i - t_{i-1})$$

$$K' = \frac{F - C \cdot v}{\rho} = 7754[N/m^3] \qquad (5.11)$$

$$C = 500[N \cdot s/m]$$

In eq.5.11, F is the soil tool interaction force, v the speed of the tool processing the ground (subscripts indicate the instant at which the speed refers to) and A is the area of the tool. C is damping coefficient and K' is the modified elastic coefficient. I extrapolated values for those from empirical data reported in the literature mentioned above. ρ is the volume of soil moved per time. A logical scheme of the work carried out during the tractor unit design is reported beside (fig, 5.74). This work package led to a second iteration of the design, the tractor unit redesign, described in the next chapter. After completing the redesign I developed the first tractor unit prototype.

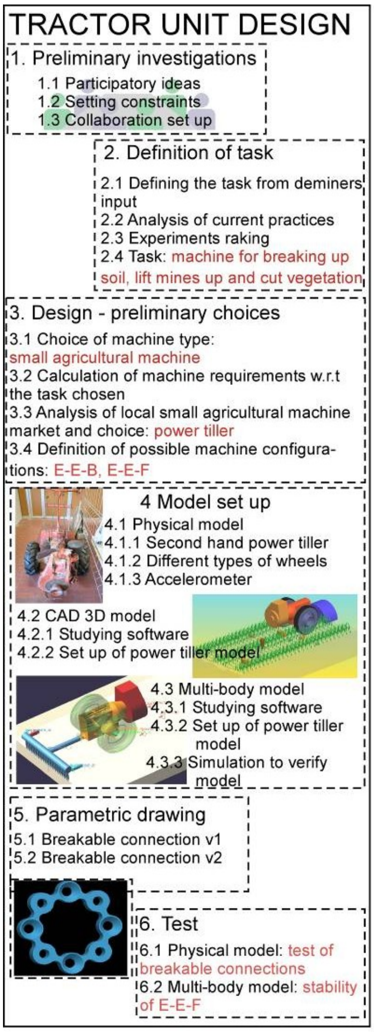


Fig.5.74. Logical scheme of the work on the tractor unit (first iteration).

Chapter 6 Tractor unit re-design

- Tracked remotely controlled platform
- Structural changes
- Frame design and prototype
- Wheel design and prototype
- Hitch system design and prototype

6.1. Tracked remotely controlled platform: concept and choice of brakes

The redesign of the tractor unit includes the design of the frame supporting the tools and the front wheels, the design of a tensioning system for the tracks, the choice of rubber tracks and the design of open cage wheels working as sprockets for the tracks. Moreover, it also includes the design of the front attachment for the ground processing tool.

The detailed design of these components was done taking the power tiller Pasquali PL CV10 (7.5kW) available at the University of Genova in mind. Although this is similar to the power tiller that will be used in Sri Lanka, modifications to the current design will be necessary and will be hopefully implemented in the field together with deminers before developing the second prototype in a local workshop, making use of the experience gained in Italy.

Both Pasquali and Dongfeng powertiller present two attachments where the frame could be connected, one where the power take off (p.t.o) is and one in front of the machine (fig.6.1).

Fig.6.1. Powertiller possible attachments for frame.

The tractor unit redesign has also to include actuators needed to drive the machine from a safe distance through remote control. Powertillers have no brakes and are driven manually by acting on handlers. Turning is achieved directly by pushing handler right or left while acceleration (I), clutch (L), gears (D), direction of motion (C) are changed by acting on cables and levers, placed on the handler. Also differential (F) and p.t.o.(E) can be inserted by acting on levers (see fig.6.2).

After having started the machine manually, while keeping clutch pressed, the first gear is inserted and forward/backward motion selected. After this, the clutch is released causing wheels to start rotating. The operator walks behind the machine holding the handler and adjusting the acceleration according to working needs. When direction needs to be changed, firstly the differential is unlocked to allow non-synchronized movement of the wheels. Direction is manually changed acting on handlers. When the power tiller is moving in proper direction the differential can be switched off to preserve the direction.

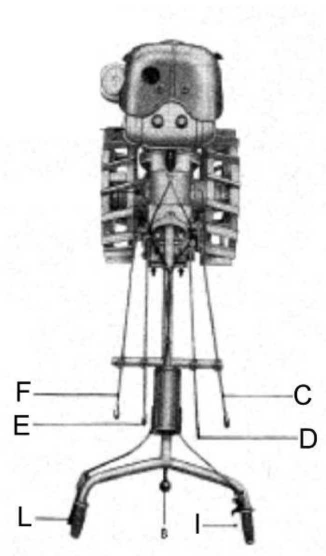


Fig.6.2. Powertiller Pasquali, levers and cables (adapted from Powertiller instruction manual, 1944).

After having analyzed manual operations, I needed to select the features to actuate by control system. All existing levers can be automated but stopping and changing direction, which is usually performed by the operator, raised up a problem. As a solution, I considered external braking system. This is a very simple system and allows exploiting brakes commonly used in vehicles and largely available also second hand. Apart from allowing stopping the machine, brakes can be used for turning, using what is called skid or differential steering. When differential is unlocked and wheels can rotate at different speed, one of the brakes can be applied decreasing the speed of one wheel. This causes the direction to change proportionally to the difference in wheel speeds. After reaching the proper direction, the brake should be released and differential switched off forcing synchronous motion.

Therefore to allow remote control, the only components I had to add were brakes; levers and cables could be actuated by either pneumatic or hydraulic cylinders.

While the implementation of the control system, including the choice of components, the design of the electrical system and circuit boards and the programming of controller have been subject of final project of three master students I have only been supervisor of, and are briefly presented in chapter 8, the design of brakes is treated in this chapter, as it affects the performance of the tractor unit. The choice of brake type and the calculation of brake forces have also been done together with master students. Their involvement in the project was very good and their help is here greatly acknowledged. Discussions and participatory tools, used since the first meeting for participatory deciding how to assign projects to students, have been helpful in achieving good results and forming a strong team. At the end of their project, we wrote a paper about the control system [6.1] and went together to Croatia to present it at the Sibenik international symposium on humanitarian demining 2007, specially targeting mechanical demining.

After comparing their performance and suitability to fit the powertiller structure with other types of brakes, we chose to employ disc brakes. They are very simple to mount on the powertiller with only little adjustments: discs can be fixed on stub axles and the relative floating callipers on appositely designed fixtures, mounted on the powertiller chassis.

Before appreciating the different systems, it was important to understand the common principles that braking systems use when stopping a vehicle: friction and heat. By applying resistance, or friction, to a turning wheel, a vehicle’s brakes cause the wheel to slow down and eventually stop, creating heat as a by-product. The rate at which a wheel can be slowed depends on several factors including vehicle weight, braking force and total braking surface area. It also depends heavily on how well a brake system converts wheel movement into heat (by way of friction) and, subsequently, how quickly this heat is removed from the brake components. Moreover the selection of any braking system for a specific application depends mainly on its friction and heat characteristics, complexity, market availability, cost, compatibility and working environment. This is where the difference between braking systems becomes pronounced.

Generally, brakes used in vehicles belong to two types: drum and disc brakes. While motorbikes can use one or the other, generally cars employ drum brakes on rear wheels and disc brakes at front. Drum brakes (fig.6.3) are brakes in which the friction is caused by a set of shoes or pads that press against the inner surface of a rotating drum. The drum is often inside the wheel, rigidly connected to it. Brake shoes are made of a heat-resistant friction material similar to that used in clutch pedals.

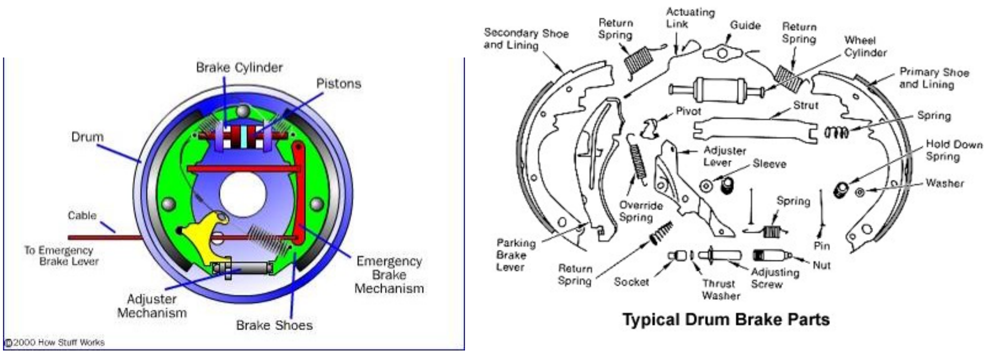


Fig.6.3. Drum brake (source: howstuffworks, http://www.familycar.com/brakes.htm).

Either a fluid or a cable is used to transfer the movement of the brake pedal or lever into the movement of the brake shoes. Drum braking systems are usually complex due to the high number of small components, difficult to assemble and service. Their cost is limited and their availability high.

Disc brakes (fig.6.4) have a simpler design compared to drum brakes. They use a slim rotor and a small caliper to halt wheel movement. Within the caliper are two brake pads, one on each side of the rotor, that clamp together when the brake pedal is pressed. Fluid is used to transfer the movement of the brake pedal or lever into the movement of brake pads.

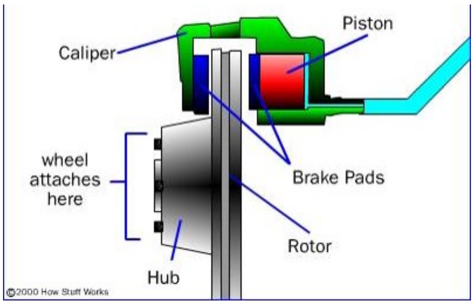


Fig.6.4. Disk brake (source: howstuffworks)

The simpler design and assembly of disc brakes make them more suitable to the application on the powertiller. Even if they cost more than drum brakes, their wide use makes them easily available second hand. Before choosing which type of disc brakes to buy and mount on the powertiller, we calculated the force required to brake and turn the tractor unit.

Under manual control, stopping is achieved by pressing the clutch, while applying a braking force opposite to motion on the handler. When clutch is pressed, wheels are decoupled from the engine and no more driving torque is applied to them; this allows the operator to apply only a small braking force on the handler. This braking force can be calculated from the work energy theorem, considering that the work the braking force has to do to stop the machine along the stopping distance is equal to the difference in kinetic energy of the machine. As the final kinetic energy is zero, as the machine is stopped, the work done by the braking force is equal to the kinetic energy of the machine before the braking system applies.

$$W = \Delta E_k;$$

$$\int_s \vec{F_f} \cdot d\vec{s} = \frac{1}{2} m \cdot v^2 \qquad (6.1)$$

Where, W is the work done by the breaking force F_f, E_k is the kinetic energy of the machine, s is the braking distance, m is the mass, v is the tractor unit speed before brakes are applied.

Considering that, when differential is locked the tractor unit goes straight, the braking force is parallel to the braking distance vector and their scalar product is equal to the product of vector modules. Moreover, considering a constant braking force, the equation above can be rewritten in function of the braking force (eq.6.2).

$$F_f = \frac{\frac{1}{2} m \cdot v^2}{s_f} \qquad (6.2)$$

Therefore, the braking force is proportional to the mass of the machine and to the original speed, while inversely to the braking distance.

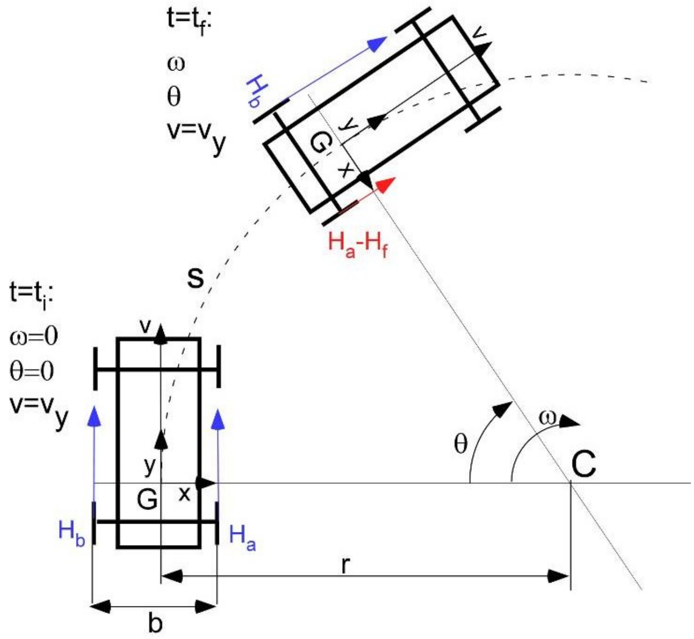


Fig.6.5. Tractor unit model for calculating the steering force.

For obtaining the expression of the braking force for steering the machine, later referred to as braking-steering force H_f, in function of steering radius r we considered first the simplified model in fig.6.5, representing the tractor unit as a four wheeled platform, with no tracks and no ground processing tool at the front, turning, for effect of the braking force applied to the internal brake A, around a centre of rotation C.

While later we introduced terms allowing to consider the influence of tracks and ground processing tool on the force to apply on brake A to have a certain curvature radius, we kept the simplifying hypotheses of having speed always tangent to the middle plane of the platform and therefore the centre of rotation on the perpendicular to the platform, passing though the centre of gravity G, and having pure rotational motion with no slip.

Under manual control, turning is achieved by applying a steering force on the handler, after having unlocked the differential. When differential is unlocked, wheels can rotate at different speed; when handler is pushed sideways, the internal wheel is forced to rotate slower than the external wheel and the powertiller turns. The steering-braking force to be applied on the internal wheel, to make it rotating at slower speed with respect to the external wheel can be calculated again using the work energy theorem, considering that the work the steering- braking force has to do to slow down the internal wheel along the steering curve is equal to the difference in kinetic energy of the machine.

$$W = \int_s \overrightarrow{H_f} \cdot \vec{ds} \tag{6.3}$$

Where, W is the work done by the steering- braking force H_f, and s is the braking distance. Considering that for hypothesis the platform is always perpendicular to the steering radius, the steering- braking force is parallel to the braking distance vector and their scalar product is equal to the product of vector modules. Moreover, considering a constant steering- braking force, and the definition of radians (eq.6.4), eq.6.3 can be rewritten in function of the steering- braking force (eq.6.5).

$$\theta = \frac{s}{r} \tag{6.4}$$

$$W = H_f \cdot (r - b/2) \cdot \theta \tag{6.5}$$

The difference in kinetic energy is written in eq.6.6, where I_C is the moment of inertia of the platform with respect to the centre of rotation C. The kinetic energy of the platform when $t=t_f$ is rotational kinetic energy. For the parallel axis theorem (eq.6.7), I_C can be written as a function of I, the moment of inertia of the platform with respect to the centre of gravity G. As it is pure rotational motion, no slip occurs, the angular velocity ω can be written as ratio between the linear speed v and the steering radius r. Therefore, the difference in kinetic energy can be rewritten as in eq.6.8.

$$\Delta E_k = \frac{1}{2} I_C \cdot \omega^2 - \frac{1}{2} m \cdot v^2 \tag{6.6}$$

$$I_C = I + m \cdot r^2 \tag{6.7}$$

$$\Delta E_k = \frac{1}{2} I \cdot \frac{v^2}{r^2} \tag{6.8}$$

Combining eq.6.5 and eq.6.8, the expression of the steering- braking force to apply to the internal wheel A can be obtained (eq.6.9).

$$H_f = \frac{\frac{1}{2} I \cdot v^2}{r^2 \cdot (r - b/2) \cdot \theta} \tag{6.9}$$

Therefore, the steering- braking force is proportional to the moment of inertia of the machine and to the original speed, while inversely to the steering radius and to the angle of curvature θ.
When considering the presence of tracks and the ground processing tool at the front of the machine, the model in fig.6.5 can be changed into the following (fig.6.6).

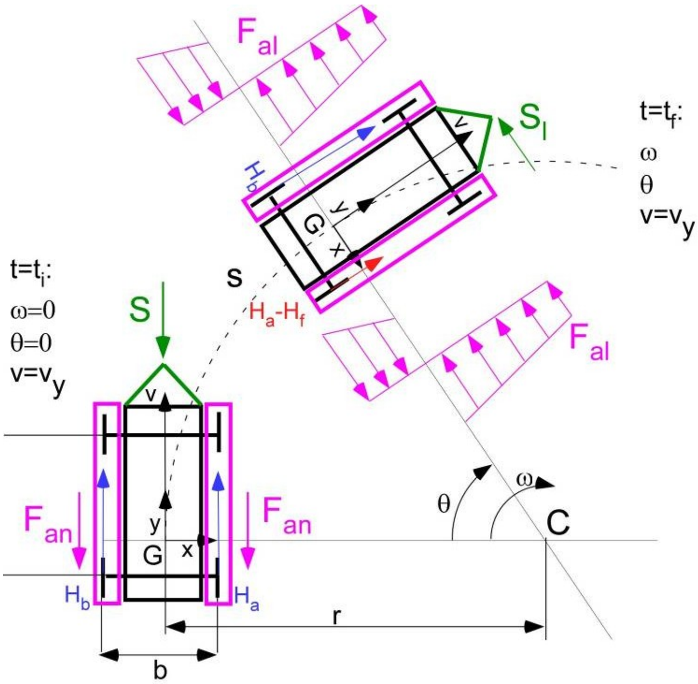


Fig.6.6. Tractor unit model for calculating the steering force when tracks and soil-tool interaction forces are considered.

As in the previous case, in $t=t_i$ the machine is in equilibrium as all forces are balanced. Therefore, here, the soil reaction forces under the driving wheels, H_a and H_b, have higher values to overcome resistance offered by the friction force between tracks and soil normal to wheel axes, later referred to as normal friction force F_{an},and the soil-tool interaction force, S.

When the steering- braking force H_f is applied, there is a change in kinetic energy of the system (the work energy theorem applies as before). But in this case, the steering- braking force is not anymore the only force that does work, as a new lateral force of friction F_{al} raises at the track-soil contact and at the tool-soil interaction S_l. Therefore, while the change in kinetic energy is still given by eq.6.8, the overall work is given by eq.6.10 and the expression of the steering- braking force is given by eq.6.11.

$$W = H_f \cdot (r - b/2) \cdot \theta - 2W_{F_{al}} - W_{S_l} \quad (6.10)$$

$$H_f = \frac{1/2 \cdot I \cdot v^2}{r^2 \cdot (r - b/2) \cdot \theta} + 2 \cdot W_{F_{al}} + W_{S_l} \quad (6.11)$$

Where, W_{Fal} is the work done by lateral friction force between one track and the ground and W_{Sl} is the work done by the lateral friction force at the soil tool interaction. They have negative sign as friction forces are always directed against motion.

The direction of lateral resistance between track and soil, F_{al}, is perpendicular to the track and opposite to the slip direction of the track as shown in fig. 6.6. By being forced to turn clockwise by the steering-breaking force H_f, around the centre of instantaneous rotation C, the part of track which is over the steering radius, along the positive axis y, will generate a lateral friction force opposite to rotation, while the part of track that is below the steering radius, on the negative axis y, will generate a lateral friction force that favours rotation.

The module of the lateral friction force between tracks and soil can be written according to Wong [6.2] as product of a coefficient of lateral friction μ_{al} and the normal force weighting on the track F_w (eq.6.12).

$$F_{al} = \mu_{al} \cdot F_w \tag{6.12}$$

The normal force weighting on the track F_w is equal and opposite to the vertical reaction force exerted by soil on the machine, V. This varies along the track length, l (fig.6.7).

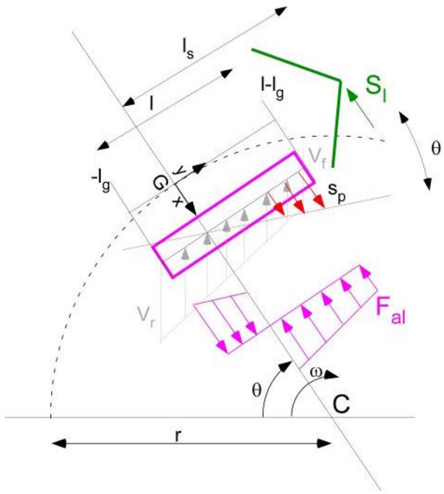


Fig.6.7. Track model for calculating the work of lateral friction force.

From equilibrium equations, the value of the vertical reaction force exerted by the soil on the machine under rear and front wheels, respectively V_r and V_f, can be found in function of the overall weight of the machine on each track and on the position of the centre of gravity l_g. Assuming a linear distribution of force under the track eq.6.13 can be written to represent the normal force weighting on the track per unit length of the track. Therefore the lateral friction force between track and soil has the same linear distribution and can be written as in eq.6.14.

$$F_w(y) = \frac{V_f - V_r}{l}(y + l_g) + V_r \tag{6.13}$$

$$F_{al} = \frac{1}{l}\cdot\int_{-l_g}^{l-l_g} F_{al}(y)\cdot dy = \int_{-l_g}^{l-l_g} \mu_{al}\cdot F_w(y)\cdot dy = \mu_{al}\int_{-l_g}^{l-l_g} \left(\frac{V_f - V_r}{l}(y+l_g)+V_r\right)\cdot dy \tag{6.14}$$

The work done by the lateral friction force between tracks and soil is along the slip direction of track s_p, perpendicular to the direction of the machine (fig.6.7). The amount of slip the friction force does varies along the track length with the distance from the steering radius, with a law that can be written as in eq.6.15. Therefore, the work done by the lateral friction force between track and soil is given by eq.6.16.

$$s_p = y\cdot\theta \tag{6.15}$$

$$W_{F_{al}} = \frac{1}{l}\cdot\int_{-l_g}^{l-l_g} W_{F_{al}}(y)\cdot dy = \int_{-l_g}^{l-l_g}\int_{\theta} \mu_{al}\cdot F_w(y)\cdot y\cdot d\theta\cdot dy = = \mu_{al}\cdot\theta\cdot\int_{-l_g}^{l-l_g} F_w(y)\cdot y\cdot dy \tag{6.16}$$

The work done by the lateral friction force between track and soil is proportional to the coefficient of lateral friction between the track and the soil, to the angle of curvature, to the length of tracks and to the weight of the machine.

The work done by the lateral friction force at the soil tool interaction can be calculated using the same considerations done for the lateral friction force at track-soil interaction.

In this case, we can generally think about a soil tool interaction force concentrated and applied in the middle plane of the machine. This force is generally not laying in the x y plane, but it is angulated by an angle, known once the raking angle of the ground processing tool is known (see paragraph 7.4). Therefore, we can write the lateral frictional force at track-soil interaction as in eq.6.17, analogous to eq.6.12.

$$S_l = \mu_{sl}\cdot S_n \tag{6.17}$$

Where, μ_{sl} is the coefficient of friction at soil tool interaction and S_n is the component of the soil tool interaction force normal to the xy plane.

The work done by the lateral friction force at the soil tool interaction is along the slip direction of the tool, the same as the slip direction of the track s_p, perpendicular to the direction of the machine (fig.6.7). The amount of slip the friction force at the soil tool interaction does is proportional to the distance from the steering radius, with a law that can be written as in eq.6.18, analogous to eq.6.15. Therefore, the work done by the lateral friction force at the soil tool interaction is given by eq.6.19.

$$s_p = l_S \cdot \theta \tag{6.18}$$

$$W_{S_l} = \mu_{sl} \cdot S_n \cdot \theta \cdot l_S \tag{6.19}$$

The work done by the lateral friction force at the soil tool interaction is proportional to the coefficient of lateral friction between the tool and the soil, to the angle of curvature, to the distance of the tool tip from the centre of gravity l_s and to the soil tool interaction force.

Values for braking force and steering-braking force, could be obtained only after completion of the tractor unit and ground processing tool design and models. Values of total weight, position of the centre of gravity, moment of inertia, distance of ground processing tool tip from the centre of gravity, soil tool interaction force and track length were not known at the time we started working on the control unit and we had to decide which brakes to purchase.

Only data relative to the original powertiller provided by the factory were known and are reported in fig.6.8.

From this data we could calculate only the force necessary to brake the powertiller, estimating an overall final mass of 700kg, including tracks, frame and ground processing tool, and imposing a brake distance of 1m. Therefore, the brake system first implemented and currently mounted on the tractor unit, has only the capacity of stopping the machine, being cylinders actuating brakes dimensioned to develop only the force necessary to stop the machine, not the higher force necessary to steer the machine. Anyhow, to achieve steering only cylinders actuating brakes should be substituted with bigger ones: as described in chapter 8, the control system is complete having the control of the steering already implemented in the control interface (joystick), PLC software, electric and pneumatic systems.

Important data of powertiller Pasquali Tipo PL – CV10, Pasquali, year 1944

Engine type	Gasoline engine, 4 strokes
Power	10HP (=7.5kW)
Mass with 2 steel wheels	250kg
Steel wheel dimensions	600x140mm
I gear ratio	50
Max. travel speed in first gear	1.1km/h (=0.3m/s)

Fig.6.8. Important data of powertiller Pasquali PL CV10, from manufacturer.

The same equations for calculating the force brake cylinders have to apply to the brake system (eq.6.24) and for choosing the brake cylinders (eq.6.26), hereafter used to choose cylinders for stopping the machine in 1m distance, can be used to choose braking cylinders able to steer the machine on the desired curvature radius, by substituting the value of braking force F_f with the value of steering-braking force H_f, obtained using equations above (eq.6.11).

The force necessary to stop the machine, with 700kg mass, travelling at the maximum speed of 0.3m/s in first gear (the powertiller will always work in first gear as it is the one that gives the maximum torque on wheels, approximately 3000Nm per wheel), in 1m braking distance was calculated, from eq.6.2, approximately equal to 35N. Therefore on each wheel should be applied a braking force at soil wheel interaction F_f equal to 17.5N, the half of the total braking force.

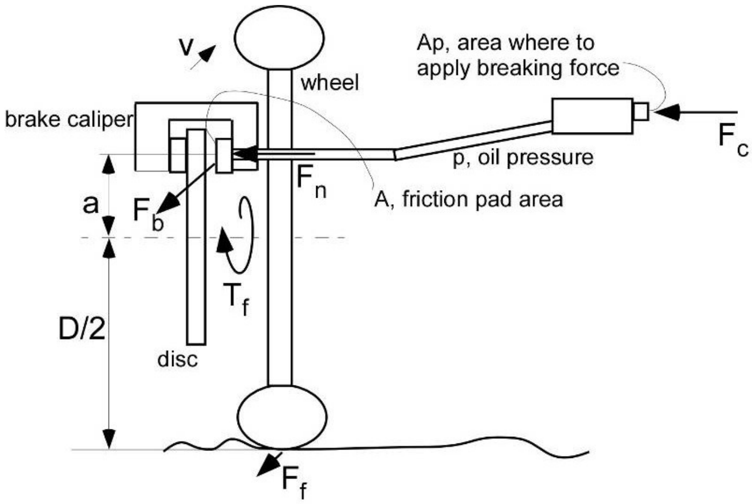


Fig.6.9. Brake system model.

Using the model in fig.6.9, the force each brake cylinder has to apply on each brake F_c, can be calculated.

Considering F_f half of the total braking force needed to stop the machine, its equivalent braking torque on the wheel axis T_f is given by eq.6.20.

$$T_f = F_f \cdot D/2 \tag{6.20}$$

This is the torque the braking system has to apply to the disc, rigidly connected to the wheel. The friction force the calliper has to apply to the disc F_b is therefore given by eq.6.21

$$F_b = \frac{T_f}{a} \tag{6.21}$$

Where, a is the distance of the pad from the wheel axis. F_b is a friction force that can be written in function of the normal force applied to friction pads and to the friction coefficient, as in eq.6.22.

$$F_b = 2 \cdot \mu_{pad} \cdot F_n \tag{6.22}$$

The friction force is multiplied by 2 as there are two identical friction pads in each calliper. F_n is the normal force applied on pads by the oil in the braking system; knowing the area of friction pad, we can calculate the pressure that has to be applied to pads by the oil, using eq.6.23.

$$p = \frac{F_n}{A} \tag{6.23}$$

Ignoring the multiplying factors inside the brake system, as worst case, the force the brake cylinder has to apply to the system F_c, for generating the breaking force at soil wheel interaction F_f, is given by eq.6.24.

$$F_c = p \cdot A_p = \frac{F_n}{A} A_p = \frac{F_b}{2 \cdot \mu_{pad}} \cdot \frac{A_p}{A} = \frac{\dfrac{F_f \cdot D/2}{a}}{2 \cdot \mu_{pad}} \cdot \frac{A_p}{A} \tag{6.24}$$

Therefore, to choose which brakes to buy, we had to consider three important parameters: friction pad area (A), area where to apply actuating force (Ap) and disc diameter (a). Disc diameter was important also because it had to fit to the powertiller existing structure.

We decided to employ disc brakes commonly mounted on Vespa ET4 motorbike, we could buy cheaply second hand. They fit well with powertiller existing stub axles and are widely available in Italy. They have the characteristics reported in fig.6.10.

Disc brakes, Vespa ET4

Friction pad dimensions and area, A	30x35mm, A =1050mm2
Diameter of surface where to apply breaking force and Area, Ap	10mm, Ap =78.54mm2
Distance of brake pads from wheel axis, a	a = 100mm

Fig.6.10. Brake system model.

Using eq.6.24, we calculated the force each cylinder has to apply to each brake F_c for stopping the powertiller in 1m, when original wheels 600mm in diameter are mounted, as equal to approximately 7N. We considered a coefficient of friction equal to 0.3, taken from the table in fig.6.11. Braking cylinders currently mounted on the tractor unit have 20mm bore diameter and

8mm internal rod. As the control system operates at 6bar (=0.6MPa), they can produce a force of 158N, more than needed.

Material	Friction Coefficient f	Maximum Pressure p_{max}, psi	Maximum Temperature Instantaneous, F	Maximum Temperature Continuous, F	Maximum Velocity V_{max}, ft/min	Applications
Cermet	0.32	150	1500	750		Brakes and clutches
Sintered metal (dry)	0.29–0.33	300–400	930–1020	570–660	3600	Clutches and caliper disk brakes
Sintered metal (wet)	0.06–0.08	500	930	570	3600	Clutches
Rigid molded asbestos (dry)	0.35–0.41	100	660–750	350	3600	Drum brakes and clutches
Rigid molded asbestos (wet)	0.06	300	660	350	3600	Industrial clutches
Rigid molded asbestos pads	0.31–0.49	750	930–1380	440–660	4800	Disk brakes
Rigid molded nonasbestos	0.33–0.63	100–150		500–750	4800–7500	Clutches and brakes
Semirigid molded asbestos	0.37–0.41	100	660	300	3600	Clutches and brakes
Flexible molded asbestos	0.39–0.45	100	660–750	300–350	3600	Clutches and brakes
Wound asbestos yarn and wire	0.38	100	660	300	3600	Vehicle clutches
Woven asbestos yarn and wire	0.38	100	500	260	3600	Industrial clutches and brakes
Woven cotton	0.47	100	230	170	3600	Industrial clutches and brakes
Resilient paper (wet)	0.09–0.15	400	300		PV < 500 000 psi · ft/min	Clutches and transmission bands

Fig.6.11.Characteritics of friction materials for brakes and clutches (source: Friction Products Co., Media Ohio).

The maximum braking force at soil wheel interaction each brake can apply is given by the maximum pressure friction pads can bear. This is for dry sintered metal between 300 and 400psi (400psi = 2.7579MPa), also given in table in figure 6.11. Therefore, using eq.6.25, obtained from previous equations, we calculated the maximum braking force at soil wheel interaction, when wheels have 600mm diameter, as equal to approximately to 580N.

$$F_{f\,\max} = \frac{2 \cdot \mu_{pad} \cdot p_{\max} \cdot A \cdot a}{D/2} \qquad (6.25)$$

The maximum braking force at soil wheel interaction F_{fmax} can be obtained employing pneumatic cylinders, alimented with compressed air at 6bar (=600000Pa), with 32mm bore diameter and 12 internal rod diameter.

This value was obtained by using eq.6.24 for calculating the force the brake cylinder has to apply to the system F_c, when we want a braking force at soil wheels interaction F_f equal to F_{fmax} equal to 580N, and putting it into eq.6.26.

$$A_c = \frac{D_c^{\,2} - d_c^{\,2}}{4} \cdot \pi = \frac{F_c}{p} \qquad (6.26)$$

Where, A_c is the internal area of the cylinder, D_c is the bore diameter of the cylinder and d_c is the internal rod diameter. The internal rod diameter d_c for a cylinder with bore diameter D_c is given in manufacturers tables.

Brake fixtures were designed by master students. Details can be found in appendix II together with all other technical drawings. They are simple and easy to assembly as it can be seen from fig.6.12.a. A double C shaped aluminium fixture holds the calliper, or clamp, and is tightened around the powertiller stub axle. The disc is simply inserted between the flange where the wheel is connected and the stub axle. Brakes are directly actuated by cylinders acting on the surface where to apply breaking force. Cylinders are fixed to a frame allowing only relative motion of cylinder shaft (fig.6.12.b).

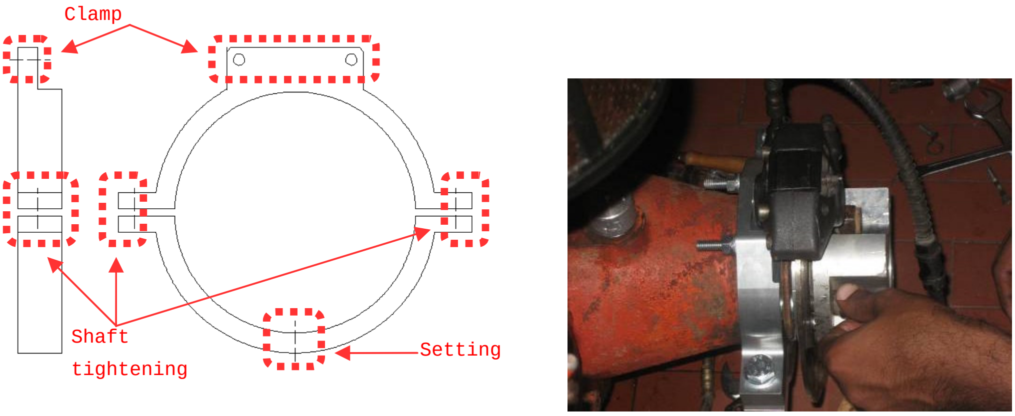


Fig.6.12.a.Brake fixtures conceptual design and assembly.

Fig.6.12.b .Brake fixtures conceptual design and assembly.

6.2. Structural changes: design variable choices

Modifying the power tiller by adding two additional front wheels, tracks and a ground engaging tool at the front affects weight transfer and the whole performance of the system.

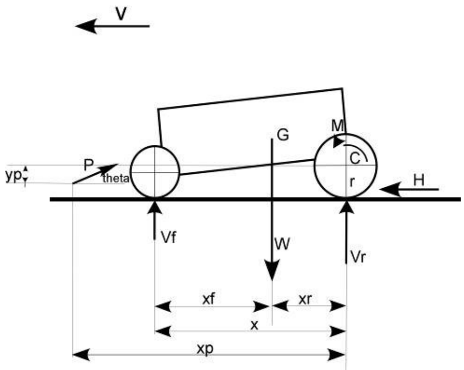


Fig.6.13. Tractor unit model.

To analyze the performance of the new system, I created a model (fig.6.13), in first approximation simply modeling the tractor unit as a four wheel tractor. To take into the consideration the actual presence of tracks, I increased the drawbar pull resulting from equilibrium equations by a factor of four, obtained by analyzing performances of the same tractor with wheels and with tracks, found in literature [6.3].

Considering the hypothesis of constant velocity, soil reaction forces under the front and the rear wheels can be calculated from equilibrium equations:

$$V_f = W\frac{x_r}{x} - P\cos\theta\frac{r-y_p}{x} - P\sin\theta\frac{x_p}{x} \tag{6.27}$$

$$V_r = W(1-\frac{x_r}{x}) + P\sin\theta(\frac{x_p}{x}-1) + P\cos\theta\frac{r-y_p}{x} \tag{6.28}$$

Where, the drawbar pull P is generally given by the difference between tractive force H and rolling resistance R:

$$P = H - R \tag{6.29}$$

While the tractive force H is generally associated with shear stress on soil, the rolling resistance R is associated with energy losses due to deformations of the wheel (elastic) and soil (plastic).

These forces can be theoretically calculated through complex expressions function of many parameters typical of the soil that are difficult to measure when not in the field and anyway differ from site to site. Nevertheless, from these formulas, a general understanding of the influence of design variable values on the force value can be obtained. Generally, the tractive force increases as the contact area between the machine and soil increases and as the total weight increases; rolling resistance increases as the dynamic weight on the wheel increases and as the wheel diameter decreases.

Using an empirical approach, instead, I was able to calculate the drawbar pull P as function of only one soil parameter, the cone index CI, measuring the resistance opposed by the soil to the penetration at the constant speed of 30mm/s of a circular cone of base area of 322mm^2 and cone angle of 30°. Another expression of P, analogous to (6.29) is given in (6.30):

$$P = V_r \cdot \psi - V_f \cdot \rho \tag{6.30}$$

Where, Vr is dynamic weight on rear wheels, Vf is dynamic weight on front wheels, ψ is the tractive coefficient for rear driving wheels, defined as ratio between the drawbar pull and the dynamic weight on driving wheels, and ρ is the rolling coefficient for front wheels, defined as ratio between the rolling resistance and the dynamic weight on front wheels.

Empirical expressions for ψ (6.32) and ρ and (6.33) were found by Gee-Clough in 1978 for wheels on agricultural soil in function of a dimensionless number called the tire mobility number M (6.31), function of the cone index CI, weight on tire W, tire width b, tire diameter D, tire section height h and tire deflection under weight δ.

$$M = \frac{CI \cdot b \cdot D}{W_w} \sqrt{\frac{\delta}{h}} \frac{D}{D + 0.5 \cdot b} \tag{6.31}$$

$$\begin{aligned} \psi &= \psi_{\max}(1 - e^{-k \cdot i}) \\ \psi_{\max} &= 0.796 - \frac{0.92}{M} \\ k &= 4.838 + 0.061 \cdot M \end{aligned} \tag{6.32}$$

$$\rho = 0.049 + \frac{0.287}{M} \tag{6.33}$$

By substituting equations (6.27) (6.28) in (6.30) I obtained an expression of the drawbar pull P in function of tractor unit design variables indicated in fig. 6.13.

$$P = \frac{W\left[\psi(1 - \frac{x_r}{x}) - \rho \frac{x_r}{x}\right]}{1 - \psi[\sin\theta(\frac{x_p}{x} - 1) + \cos\theta \frac{r - y_p}{x}] - \rho[\cos\theta \frac{r - y_p}{x} + \sin\theta \frac{x_p}{x}]} \tag{6.34}$$

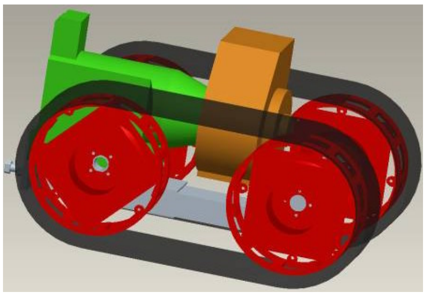
$$P_{tracks} = P \cdot 4$$

As previously said, I used the multiplier 4, to take into the consideration the actual presence of tracks. Therefore the drawbar pull of the tractor unit can be approximately estimated once the values of the following tractor unit design variables are known:

- x_r, distance of centre of gravity from rear wheel
- x, distance between axles (in tracks assembly, length of tracks)
- r, radius of rear wheel
- y_p, vertical distance of point of application of P wrt C
- x_p, horizontal distance of point of application of P wrt C

- θ, angle by which P is inclined wrt the ground
- W, total weight of power tiller.

Using the model in fig.6.13 and the mass properties of 3DCAD model, of which the one in fig.6.14 represents the final version, I obtained a first estimation of the drawbar pull P on the horizontal, at ground level, of approximately 3000N, on soil characterized by a CI value of 500kPa, typical of Sri Lanka (see paragraph 4.2.3).



Mass properties of the model

m = 500kg

distance between rear and front axis, x = 758mm

distance between rear axis and centre of gravity, xr =234mm

wheel radius, r = 252mm

soil reaction force under rear wheel, Vr =3400N

soil reaction force under front wheel. Vf = 1500N

Fig.6.14. Tractor unit final model, 3DCAD with mass properties.

I used the analytical model to choose rear and front wheel diameters and tracks. I chose wheels approximately 500mm in diameter for both rear (D_r) and front (D_f) wheels. By plotting the drawbar pull resulting from eq.6.34 versus diameter ratio D_f/D_r, for the same 3DCAD model, for different soil types, i.e. different values of Cone Index CI, I obtained a general increase in drawbar pull as diameter ratio increased, more sharp for lower values of cone index, i.e. looser soils (fig.6.15).

The same diameter for front and rear wheels seemed a good compromise between drawbar pull and simplicity: having only one type of wheel makes maintenance easier as wheels can be interchanged and stock simpler. Moreover, bigger front wheels allow overcoming bigger obstacles.

To choose tracks, I considered their floating capacity and traction. Tracks can float if the pressure they exert on soil is lower than the pressure the soil can bear. As reference value for pressure the soil can bear I used the cone index value of 500kPa and I calculated the pressure tracks exert on soil as ratio between the overall weight applied to them, therefore the weight of the tractor unit and area of tracks. Tractive capability is related to the pressure tracks exert on soil and good traction is generally considered to be achieved when pressure is between 0.01 and 0.02MPa, according to the producer. I chose commercially available rubber tracks 200x72x47, 200mm width, having an overall length of 3384mm. Unfortunately these were not readily available in the shop and a pair of tracks equal but 230mm wide were kindly provided for free by the Italian company Minitop (fig.6.16). Considering the weight of the final model designed with pro Engineering 3DCAD software, approximately equal to 500kg and distance between rear and front axle equal to 758mm, with wheels 500mm in diameter, the pressure these tracks exert on soil is

0.014MPa, within the range of good traction and far less than 0.5MPa (=500kPa), the pressure the soil can bear.

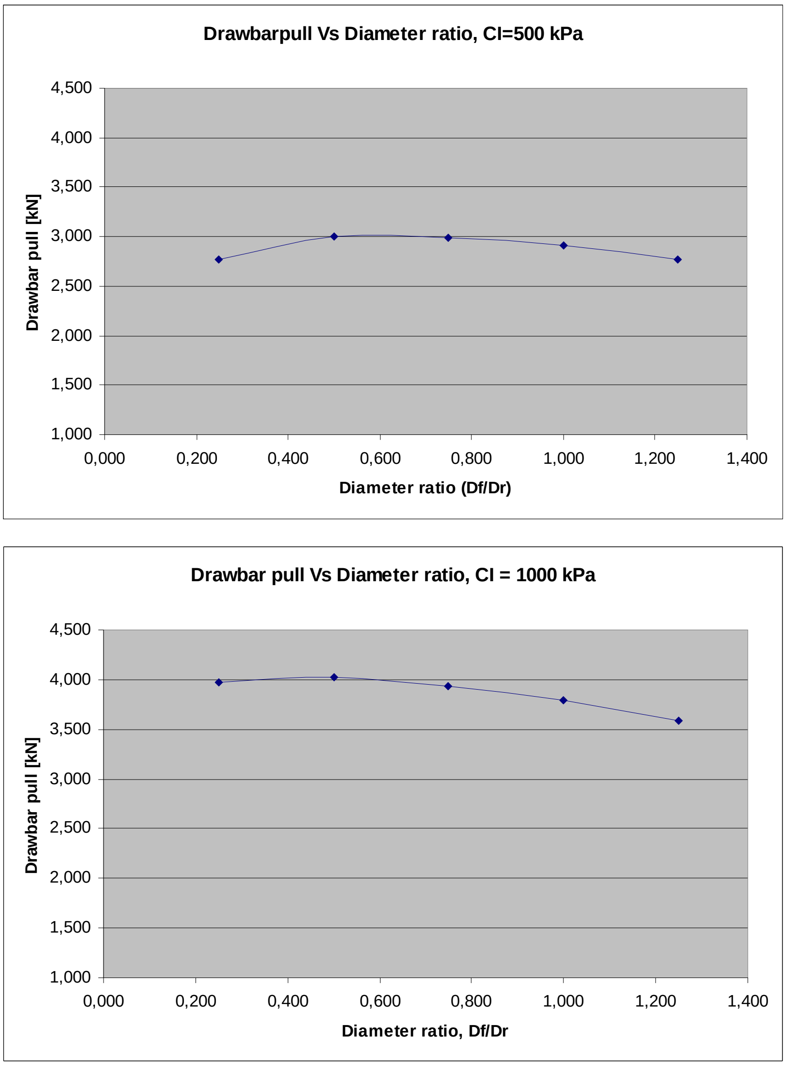


Fig.6.15. Drawbar pull P[kN] versus diameter ratio Df/Dr for different soils.

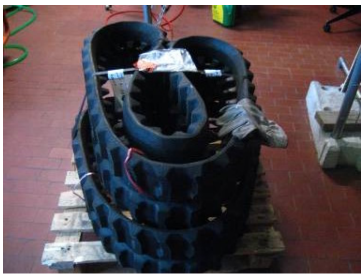


Fig.6.16. Tracks, 230x72x47, kindly provided for free by Minitop.

In second approximation I developed a refined analytical model, taking into account the presence of tracks instead of wheels. In the first model I treated the tractor unit as four wheel machine, and

I considered the effect of tracks generally as increasing the overall drawbar pull four times. In fact, the assumption of having only driven wheels at rear is not true anymore having both rear and front wheels contributing to traction as well as to rolling resistance.
Therefore eq.6.35 can be used instead of eq.6.34 to estimate the maximum drawbar pull the system is able to exert:

$$P_{max} = H_{max} - (\rho_f \cdot V_f + \rho_r \cdot V_r) \tag{6.35}$$

$$H_{max} = 2A \cdot c + W \cdot \tan\phi \tag{6.36}$$

Where, H_{max} is the maximum tractive force the system can exert when tracks are locked and is given by eq.6.36. W is the total weight of the system, A is the area of contact with the ground of one track, c is soil cohesion and ϕ is the angle of soil internal friction. ρ_f and ρ_r can be obtained from the table in fig.6.17, reporting coefficients of rolling resistance versus tire diameter, considering the front wheels approaching an harder ground and the rear wheels a more loose soil.

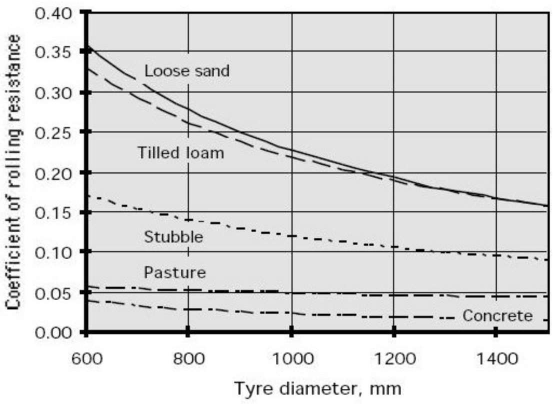


Fig.6.17. Coefficient of rolling resistance versus tire diameter on different types of soil (source: Macmillan 2000[6.3]).

For the final tractor unit model, weighting 500kg, Vr is approximately equal to 3400N, while Vf to 1500N. Considering front wheels (D=500mm) approaching pasture soil (ρ_f = 0.05) and rear wheels approaching tilled loam soil (ρ_r = 0.3), the maximum drawbar pull the tractor unit can exert, using eq.6.35, can be calculated as equal to 5200N.
Modifying the power tiller by adding the new components will cause an increase in its weight. In general, adding extra weight and enlarging the ground contact area to a tractor is desirable, especially if no idlers are to be used to keep the track in contact with the ground (to keep the frame as simple as possible) and ballast may have to be used to improve weight distribution between the front and the rear of the track. Nevertheless, adding weight could cause to have the

machine not slipping any more in lower gears before the engine gets stall. This is a form of protection as it limits the load on the transmission components: in most tractors the weight and tires are such that in the lower gears the wheels will slip before the engine stalls, while in higher gears the opposite happens. Therefore, the maximum tractive force exerted by the machine when tracks are locked, and therefore 100% slippage occurs, was calculated and compared with the maximum force the engine can generate horizontally at wheel-soil contact. I used eq.6.36 to determine the maximum tractive force for the power tiller weighing 500kg, employing the tracks chosen 230x72x47 on soil having an angle of internal friction of 30° and cohesion c =10kPa, as equal to 6300N. I compared the value obtained to the force the power tiller can generate at wheel-ground contact, horizontally. I calculated this for the power tiller Pasquali purchased in Italy, having 7.5kW power, 50 gear ratio in the first gear, 500mm wheel diameter, 1.1 km/h speed in first gear as equal to 25000N, without considering any loss. Therefore, in low gear, the engine should not stall.

6.3. Wheels detailed design and prototype

Before starting the detailed design of tractor unit wheels, I investigated the types commonly employed in tracked systems. Usually, in each track there are two types of wheels: large wheels, as large as the track, with no teeth, used for supporting weight and tensioning the track (usually these wheels are spring mounted idlers) and thin sprocket wheels engaging the holes that rubber tracks present on the middle plane.

Using the same principle adopted into the choice of the same diameter for front and rear wheels, pursuing the goal of simpleffectiveness by reducing the number of specialized components to add to the powertiller, I decided to design only one type of wheel, solving the double function of sustaining the track and working as a sprocket propelling the track forward. Therefore, I designed a single wide wheel with teeth to be mounted on the two original driven stub axles and on the two new stub axles added at the front. For increasing simplicity, I also decided to design the new wheel as similar as possible to off the shelf agricultural wheels, in order to exploit facilities existing in factories producing them and to lower the manufacturing cost. I used the same C shaped rims of open cage steel wheels commonly used in agriculture (fig.6.18). Instead of externally welded oblique lugs, commonly used, I added new lugs, designed to engage the internal track pattern, to be welded internally (fig.6.18). This design allows the C shaped rims to support the track externally and the lugs to drive the track forward by acting on the internal track teeth.

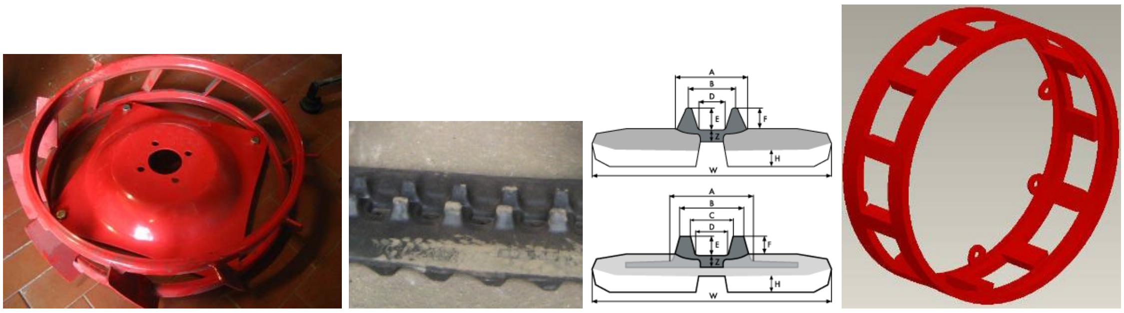


Fig.6.18. Agricultural open cage wheel, track and new wheel design, rims and lugs.

Wheels measure 504mm in diameter. While a diameter near to 500mm was chosen from previous considerations, I have chosen this particular value to have an entire number of lugs (12) and a simple angle (30°) between lugs. In fact, as the frame, wheels were welded in a not specialized workshop, where very high precision quotes were impossible to achieve. Experienced blacksmiths could easily assembly and weld lugs, 30° apart, with high precision and poor tools.
On the combination between the number of lugs and the diameter, depends the capability of the wheel to match exactly the track. I decided to engage one lug every 2 track modules. Each track module (m) is 72mm long, on the middle plane at half thickness; track is 45mm thick. Therefore, the length of the arch (l) described by a module of the track around the wheel with 504mm diameter (D) is given by eq.6.37 and is equal to 66mm.

$$l : m = D : D_m$$

$$l = \frac{m \cdot D}{D_m} \qquad (6.37)$$

It follows that the angle under this arch is 15° and the angle under the arch described by two track modules is 30°.Therefore, the number of lugs is 12, obtained by dividing 260° by the angle between lugs.
Initially I designed lugs shaped as trapezium based cylinders, perfectly matching track internal pattern. Before manufacturing the wheel I used crap up real scale paper prototypes (fig.6.19) to verify the design: I had the possibility to discuss it with Mr. Ross Macmillan senior academic associate in agricultural engineering and author of the book I used as reference for the tractor unit design [6.2] at the University of Melbourne who kindly accepted to work with me for one month at the University of Genova.
The complete model of wheels is pictured in fig. 6.19. I have designed flanges as similar as possible to flanges in use in agricultural open cage wheels. Technical drawings are reported in appendix II.

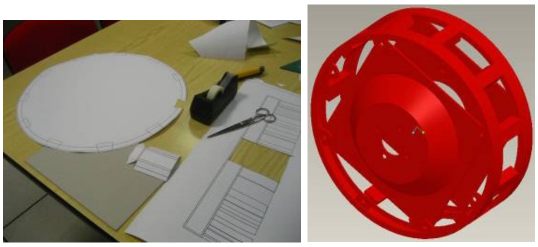


Fig.6.19. New wheel crap up prototype and complete model.

After development and test, I modified original lugs drawings, instead of trapezium based cylinders perfectly matching track internal pattern, together with people working in the workshop we decided to use simple tubes. The cylindrical shape allow easier insertion in track internal pattern teeth and because they do not match perfectly with the pattern they allow compensation of possible positioning errors. The first and second wheel prototypes are reported in fig.6.20.

Fig.6.20. Tractor unit wheel first and second prototype.

6.4. Frame detailed design and first tractor unit prototype

The frame had to satisfy the functional requirements of supporting front wheels and tracks, and supporting the ground processing tool and other tools such as the vegetation cutting tool. After having analyzed different possibilities, I decided to design a frame incorporating the track tensioning system and to make it out of standard steel profiles, easily available everywhere and easy to weld. Luckily, I had the possibility to discuss important design choices with Mr. Ross Macmillan. Before starting the design of the frame, I analysed commonly used systems for tensioning tracks. Usually, tracked vehicles foresee an individual track tensioning system (fig.6.21) that individually spring load tracks with compression spring located within the track. This arrangement allows for any difference in length of the tracks and also for vertical deformation of the tracks between the wheels when the track passes over a stone or local hump.

I considered two possible designs: a frame incorporating two individual track tensioners and a frame with a single central track tensioner, working for both tracks at the same time (fig.6.21).

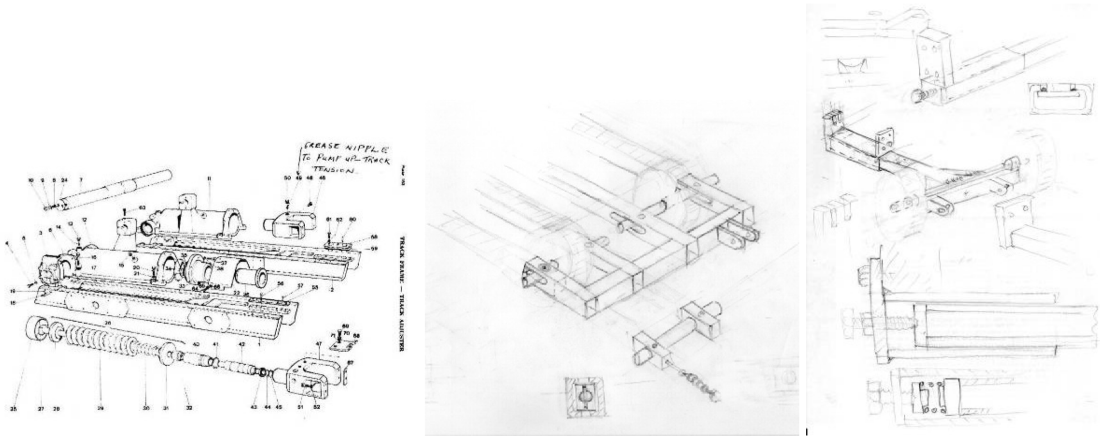


Fig.6.21.Commercial individual track tensioner and frame possible designs: individual and single central tensioner.

I opted for the second choice, being simpler and cheaper. Tracks are tensioned by pushing on the front axle member, on which the front wheels are mounted through the screw at the rear of the machine. This design is simpler and provides a near rigid arrangement by treating both tracks in the same way. Depending on the difference in length of the tracks and the evenness of the ground, this arrangement will probably be satisfactory for some time and allow a decision to be made as to whether the mechanically more complex arrangement proposed above is required for long term operation.

Before finalizing the design of the frame I analyzed several possibilities, reported in fig.6.22. The frame final design is also represented in fig.6.22 in the bigger picture: it is characterized by being all made of steel standard profiles, easy to build and to maintain as only cutting and welding of profiles available on the market is needed. It is mainly constituted by two standard profile boxes sliding one into the other. A main fore and aft frame member in the form of a rectangular hollow section, called big box, is fixed to the two mounting areas on the body of the tiller and extended forwards to the front axle member. On the same profile rearwards can be fit a ballast weight if necessary to improve the weight distribution. This main frame member has a second rectangular hollow section member, called small box, sliding within it that carries the front axle. The rear end of this is located by a large screw at the rear of the tractor which is used to tension the tracks. The front stub axles each running in two bearings is carried on the front axle member attached to the second member mentioned above. The front axle member, called T box, is a standard rectangular hollow profile having same dimensions as the big box, welded perpendicularly to the small box. Laterally two plates are welded to the T box to make it more robust.

While the length of the big box depends on the distance between the two powertiller mounting areas, a relationship exists between the length of the small box, the minimum and maximum distance between rear and front axes, respectively for mounting and tensioning the tracks, and the length of the tensioning screw. It is given in eq.6.38and 6.39. Variables are indicated in fig.6.23.

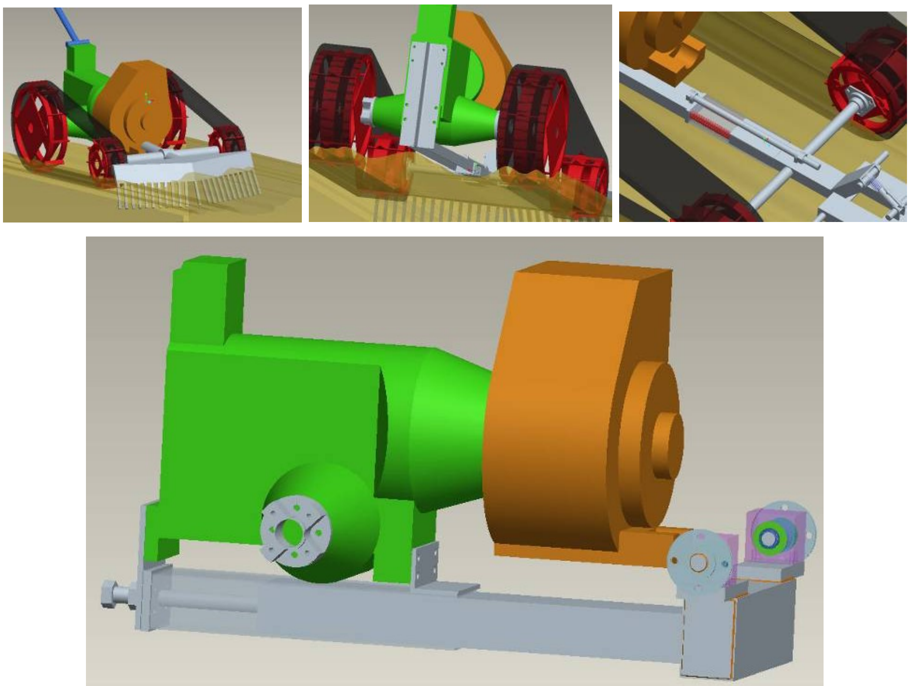


Fig.6.22. Tractor unit frame early designs and final design, model.

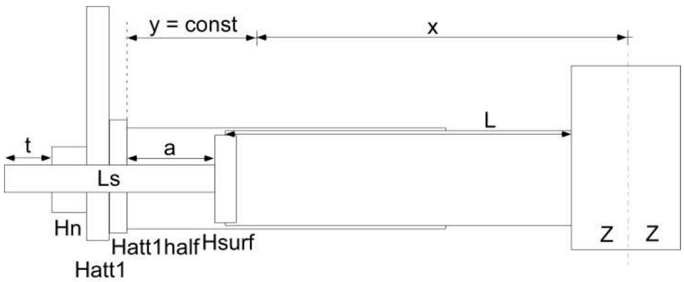


Fig.6.23. Model for calculating small box length, L.

$$x_{\max} = {H_{surf}}/{2} + L + Z + a - y \tag{6.38}$$

$$x_{\min} = {H_{surf}}/{2} + L + Z - y \tag{6.39}$$

$$t = L_s - H_n - H_{att1} - H_{att1half} - a \tag{6.40}$$

The length of small box in the complete model and in the prototype is 900mm, the length of the tensioning screw Ls is 280mm. This means having a minimum distance between rear and front axes equal to 645mm and maximum 830mm, enough for the task.

The front stub axles are mounted on the T box, a rectangular hollow section having same dimensions as the big box, T-welded to the small box. Stub axles have to allow the two front wheels to rotate independently. As for the frame, I made several design of stub axles, both with journal bearings and ball bearings (fig.6.24). Due to skid steering front stub axles bearings are subject both to radial and axial load. The radial load is the powertiller weight and axial load arises during steering. I used a radial load of 2000N, slightly more than 1500N, the vertical reaction force at front wheels V_f for the last version of the model, considering the worst case of having all weight on one stub axle. As axial load I used a force of 5300N, obtained by dividing the braking torque to the distance between rear and front axes, which is 0.758m for the last version of the model. As braking torque, I considered the maximum, obtained when the braking force applied to one wheel is completely stopping that wheel. In this case the breaking torque is given by half of the overall tractive force the engine exerts on ground, when the powertiller moves at the maximum speed of 0.3m/s in first gear, 12500N, multiplied by half of the distance between two wheels on the same axis, 0.322m. The final design of tractor unit includes two identical single row tapered roller bearings in each stub axle, mounted in “O” configuration. Their SKF code is 30206, they have internal diameter 30mm, external diameter 62mm and maximum dynamic load of 43200N. To calculate their lasting life I used the equivalent dynamic load obtained with eq.6.41 given by the producer.

$$P = 0.4F_r + YF_a \qquad (6.41)$$

Where, P is the equivalent dynamic load, F_r is the radial load and F_a is the axial load. Y is a coefficient that is found in tables. For the bearings I have chosen Y = 1.6. Therefore, the equivalent dynamic load acting on each bearing is 9000N. To obtain the bearing lasting life this value has to be inserted in eq.6.41, valid when considering a constant rotational speed, where L10h is the basic lasting life in number of hours, n is the rotational speed in revolutions per minute, p is a coefficient that for roll bearings is 10/3 and C is the dynamic load coefficient typical of the bearing.

$$L_{10_h} = \frac{1.000.000}{60 \cdot n} \cdot \left(\frac{C}{P}\right)^p \qquad (6.41)$$

Therefore, considering a rotational constant speed of 10rev/min, bearings can last for more than 200.000 hours, much more than required to bearings mounted in machines working 8h/day, 30.000 hours.

The complete design and assembly of the stub axles is reported in the bigger picture in fig.6.24a, together with earlier designs.

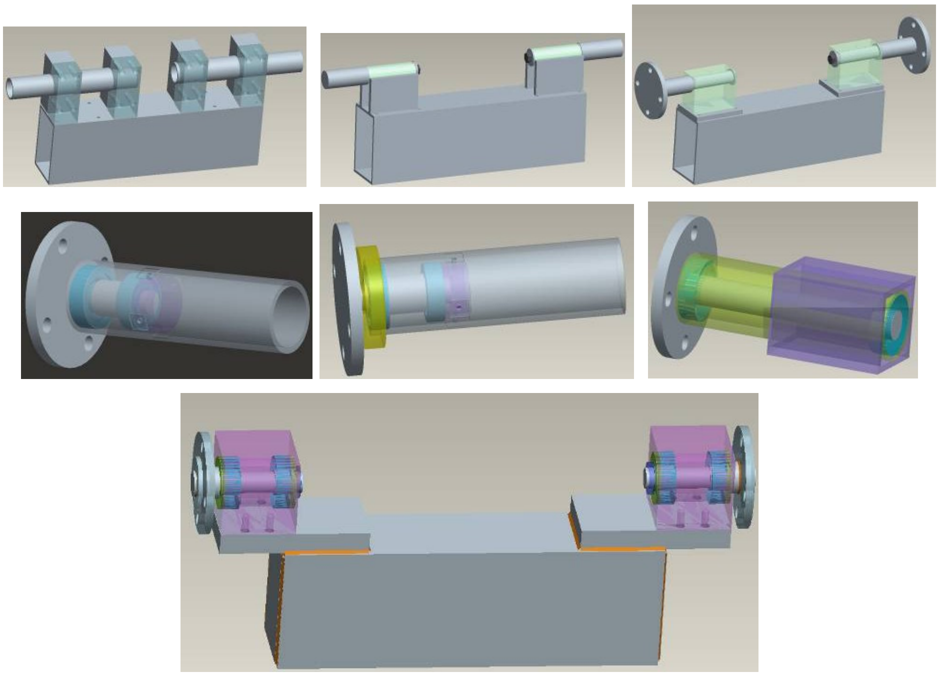


Fig.6.24.a. Stub axle model exploded and assembling.

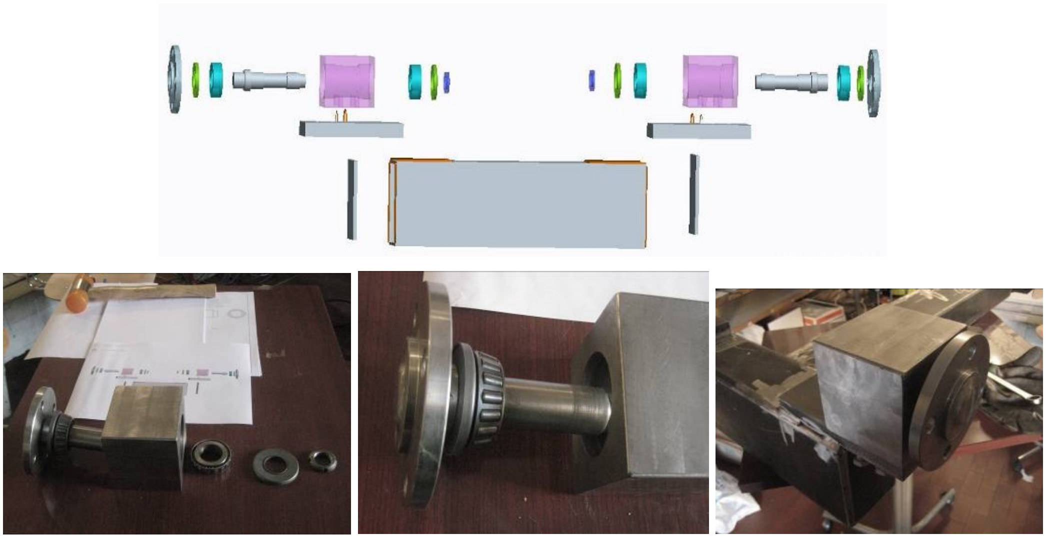


Fig.6.24.b. Stub axle model exploded and assembling.

Before finalizing the technical drawings of the frame, reported in appendix II, I performed a finite element analysis on the frame assembly, loading the t box horizontally with 2500N, the force I estimated develops at soil-tool interaction (see chapter 7). The maximum stress induced into the structure according to Von Mises failure criterion is 40MPa, much less than the yield strength of any kind of steel, the cheapest being around 200MPa. The maximum displacement is acceptable being 0.18mm.

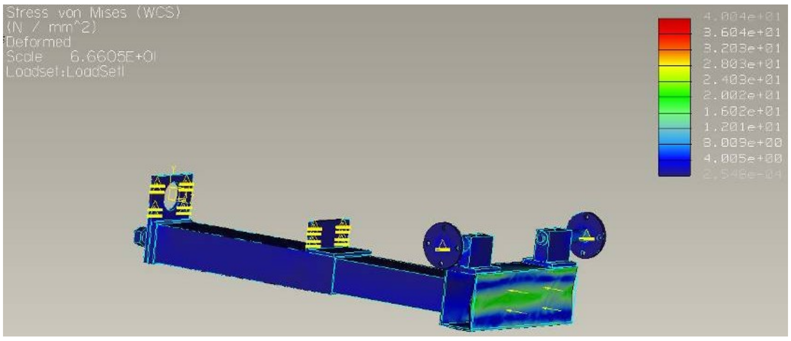


Fig.6.25. FEM analysis on frame.

During several simple tests, the tractor unit first prototype worked well. Wheels engaged tracks and propelled the vehicle forward; the frame matches well with the powertiller structure and seems robust, even if further tests, possibly in the real field will have to state it. A detailed test with proper sensors should also be performed to assess tractor unit features, such as effective drawbar pull, real weight and slip coefficient. Significant pictures taken from the video recorded during tests are reported in fig.6.27.

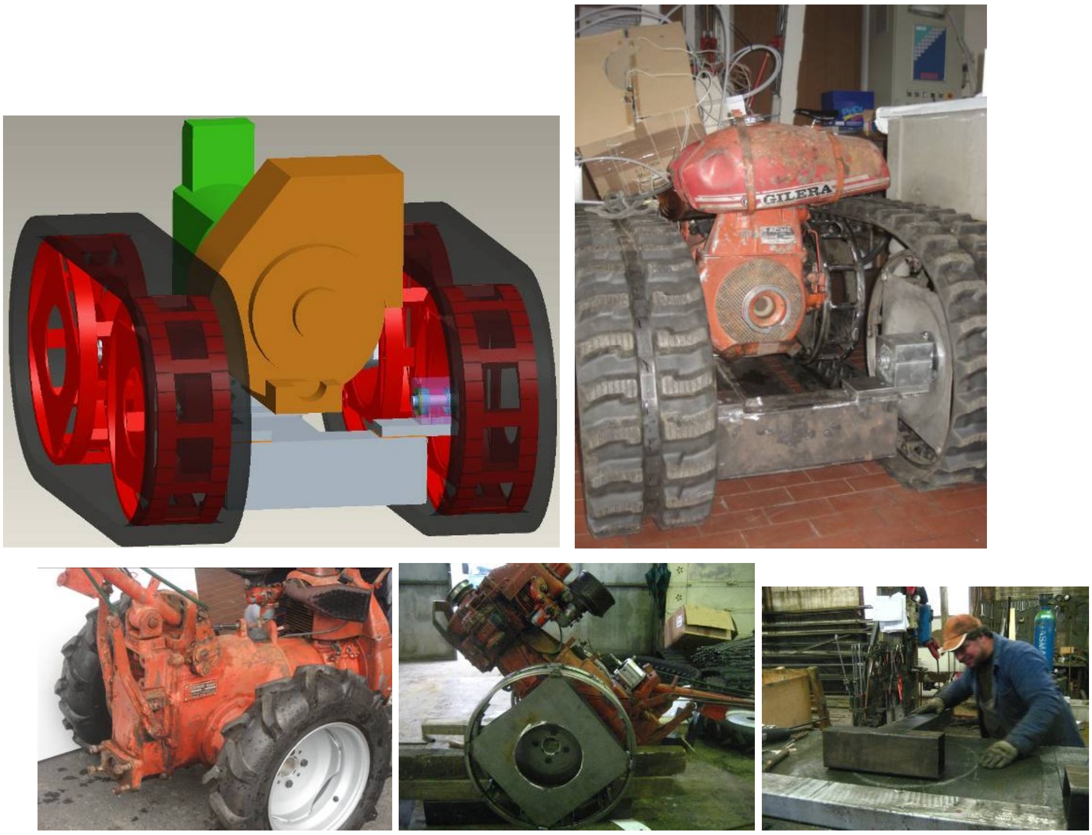


Fig.6.26.a. Tractor unit final 3DCAD model and first prototype. Assembly.

Fig.6.26.b. Tractor unit first prototype assembling.

Fig.6.27. Tractor unit first prototype during first tests.

6.5. Hitch system design and prototype

In order to attach the ground processing tool and other different tools to the tractor unit I had to design a hitch system. As the tractor unit, also the hitch system had to answer requirements of simpleffectivenss. As the tractor unit is designed to be a platform for supporting different tools for assisting different demining tasks, the hitch system had also to be as versatile as possible.
Before finalizing the design I analyzed several possibility, shown in fig.6.28, mounted on different versions of tractor unit design.

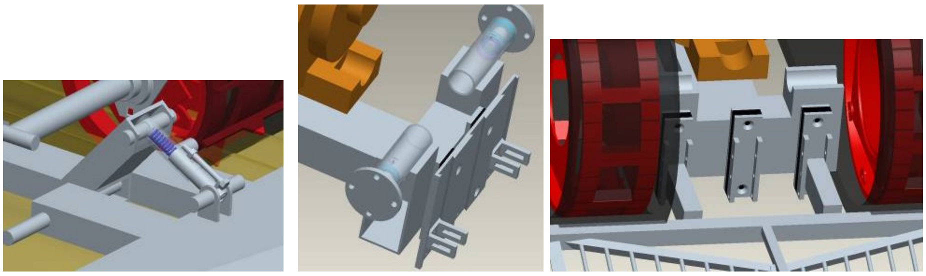


Fig.6.28. Early hitch models.

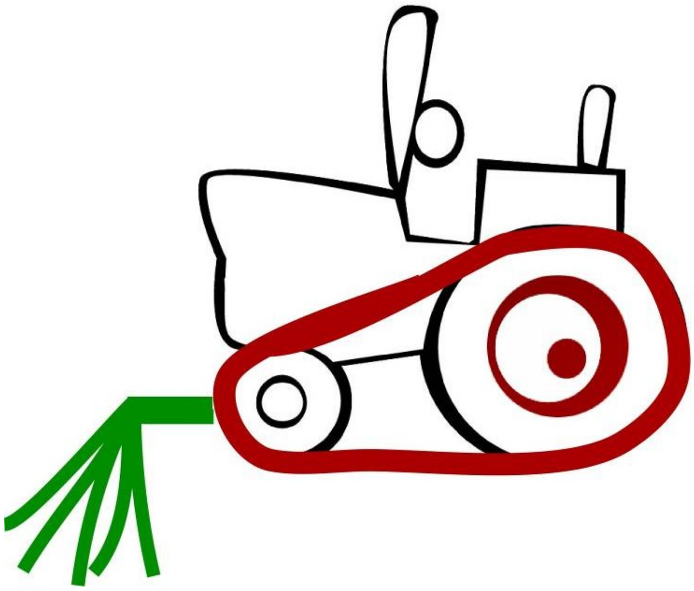
As it can be seen, the idea evolved from a spring loaded kind of three point hitch system, when the depth control wheel on the ground processing tool (chapter 7) was not in the model, to a simpler modular system, where either the clamps could be shifted up and down on vertical guides and screwed into the desired position or the tool itself could be shifted up and down inside fixed clamps. I also investigated the possibility to add simple shock absorption system such as rubber between the t box on the frame and the hitch system, but this idea turned out not to be practical after explosion tests as vibrations induced by explosions had a vary wide range of frequencies with ones transporting more energy being over 300Hz (fig.5.69) and this kind of dumpers work only for frequencies around 50Hz.

Therefore the last version of hitch system (fig.6.29) doesn't use rubber and is just welded on the t box. This is the simplest arrangement I could think. Each hitch module is made out of three thick plates welded together using the K type of welding to be more robust. The lateral force hitches have to withstand is approximately the same axial load bearings in front stub axles are loaded with, 5300N. Two modules are needed to pivot the ground processing tool to the frame while three, one at a higher position in between the lower two, can provide a rigid support to a different tool.

Fig.6.29. Hitch module final model, assembly on the model and prototype.

A set of two hitches allowing the ground processing tool to move backward and forward into suitable slots, can be used for having a vibratory ground processing tool. In this case a cylinder should be added as further connection between the tool and the frame. The same system with an L shaped slot could be used to vibrate the tool, when the cylinder reaches half way of his stroke and goes back, and to lift it when the cylinder extends completely (fig.29).

Chapter 7 Ground Processing Tool



- Ground processing aim and logic
- Soil translocation analysis
- Ground processing tool design
- Soil-tool interaction force, FEM analysis
- Ground processing tool manufacturing and test in Jordan

7.1. Ground processing aim and logic

The task of the machine is to process the soil in order to make demining activities with excavation tools easier for deminers. The ground processing tool module has to smooth the soil up to the required depth of 100mm and expose landmines by lifting them up on soil surface, possibly without actuating them. The requirements the ground processing tool has to satisfy therefore are to process the soil at constant depth and, as it is placed at the front of the machine, to remove landmines before the tractor unit passes over them.

The power tiller I'm employing as tractor unit has 7.5kW engine; due to its limited capacity, energy consumed by the ground processing module should be as low as possible; other important requirements the tool has to meet are the general ones valid for the whole machine: it should be low-cost, easy to use and maintain, robust, made of few simple parts, easy to find on the local market and able to work in dusty and dirty environment at high temperatures.

After having been lift, landmines can be disposed in two ways: they can be collected by the tool or pushed beside the machine. According to deminers' needs and the particular placement of landmines in Sri Lanka, along belts, I decided to first design a ground processing tool that, after lifting mines, leaves them beside, not collecting them. As discussed in paragraph 4.3, this allows using the machine in a sort of area reduction process, when the first landmines are exposed, and the belt therefore located, deminers can proceed to manually clear the belt without wasting energies and time working where there are no mines, while the machine can be employed to locate the belt in the next mine field (fig.7.1).

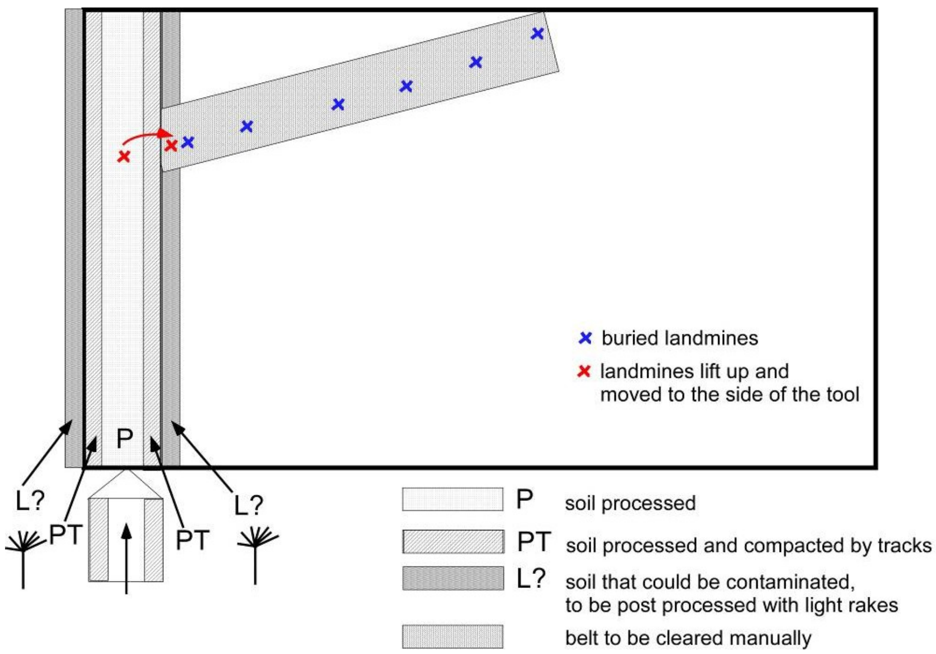


Fig.7.1. Ground Processing logic.

Therefore, deminers have to assist the machine: they will walk on its clear path using only the light rake to locate and remove landmines already lift up on soil surface by the ground processing tool, before starting actual manual mine clearance of the belt. Working on where landmines are known to be instead of processing ground where landmines are found sporadically, helps keeping a high level of concentration and gives more satisfaction, as I was personally told by a demining team in Sri Lanka. Moreover, performing area reduction means saving a lot of time; from data acquired by NPA in Angola [7.1] after having performed area reduction process, typically between 90% and 97% of a total minefield can be considered free of mines.

Other tools targeting different types of soil and working with different logic could be developed in the future and mounted on the tractor unit platform. Time allowed me to develop only the ground processing tool that is presented here.

7.2. Soil translocation in agricultural tillage tools and first design

Primary tillage is defined as the process of loosening the soil from an initial compact state by dragging a metal implement through it. This is exactly what the ground processing tool, made out of steel, to be easy repairable in a local workshop by welding, has to do. Therefore, it was of great interest to look into tillage theory before starting the design of a new tool.

Soil is a special example of granular (solid) material, containing in smaller quantities water (liquid) and air (gas). It is a three phase system extremely weak in tension, very strong in compression and in practice it fails mainly in shear [7.2]. Failure is defined by the Coulomb criterion in which the maximum shear stress is a function of the compressive stress normal to the plane of shear failure (eq.7.1).

$$S = C + \sigma \cdot \tan \varphi \qquad (7.1)$$

Where, S is the soil strength, i.e. the maximum shear stress the material can hold before failing, C is soil cohesion, σ is the normal stress and φ is the angle of internal friction.

The strength or resistance to sliding at a soil-metal interface is analogous to the resistance to shear of a soil-soil surface. The soil-metal sliding equation (eq.7.2) is similar to the soil-soil shearing equation.

$$S' = C_a + \sigma \cdot \tan \theta \qquad (7.2)$$

Where, S' is soil-metal sliding stress, C_a is tangential adhesion, σ is the normal stress and θ is the angle of soil metal resistance.

In designing soil engaging implements it is of main importance to produce efficient tools, which perform the manipulation required with a minimum effort, therefore minimum draft. Parameters that influence the draft force required to pull or push the implement in the soil are: soil/soil parameters, such as angle of internal friction and cohesion, soil/metal parameters, such as polish of the implement surface and soil moisture content, both affecting tangential adhesion, and implement shape parameters. Between these, great importance assumes the rake angle, the angle between the horizontal and the implement blade (fig.7.2). Draft force increases as rake angle increases [7.3]. Moreover, during tillage, especially tillage in which the width of cut is very large compared to the working depth, a prism of soil is separated in front of the implement and slides forwards and upwards along the failure surfaces as the implement moves forwards (fig. 7.2).

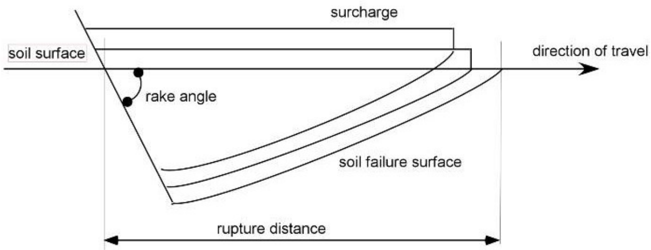


Fig. 7.2. Soil failure pattern and surcharge effect (adapted from Spoor [7.2]).

The failed soil associated with different failure surfaces build up in front of the implement producing a surcharge effect that is not desirable. This phenomenon can be attenuated if soil moves along the blade, i.e. if scouring occurs. Scouring occurs as long as the resistance at soil implement interface is less than at a parallel soil-soil interface. As generally the angle of soil metal resistance is less than the angle of soil internal friction, an increase in normal load improves scouring. Therefore, slatted implements with less surface area encourage scouring by increasing the normal load.

Low draft is a very important requirement also for the ground processing tool that is only one of the modules driven by the powertiller based tractor unit, a machine with only 7.5kW engine. For my application it is also important to increase scouring to have mines moved on the side of the machine.

In order to achieve an action similar to the one of heavy rakes and process the soil with minimum energy consume I decided to design an implement with tines.

It is shaped like an arrow to allow landmines to move sideways from the machine lane. The rake angle is less than 90° to allow approaching the landmine from the side, avoiding exerting force directly on the pressure plate, as well as for lowering the draft force. The risk of actuating landmines exists, if landmines are found upside down or if soil presents a crust on top, but in case of explosion the damage to the tool should be limited to the tines, which are simple steel rods easily repairable at low cost.

Before starting the design, I have looked into agricultural tools used to perform similar actions. In particular, I found that potato diggers solve a task very similar to the ground processing tool: they lift potatoes and leave them on soil surface. Two types exist, fixed and vibrating potato diggers (fig.7.3). Both are pulled by a prime mover at the back.

Fig. 7.3. Fixed and vibrating potato digger.

Although not directly applicable to the tractor unit because designed to be pulled and not pushed by a prime mover and because of rake angles and working depth not conceived for the demining task, potato diggers were interesting references for the design of the ground processing tool due to their close similarities, supporting the idea that demining tool could be developed and designed within any workshop producing or repairing agricultural tools.

As in the case of potatoes, vibration could also benefit the removal of mines. In soil harder than the soil usually found in Sri Lanka, a ground processing tool vibrating forward and backwards would be an advantage: the movement would facilitate sieving through tines. Both people from the mine action field and people from the agricultural machinery industry, I had the chance to discuss ideas with, saw a ground processing tool that could vibrate as an advantage for processing hard soil.

The first intuitive design of the ground processing tool I made, mounted on an early version of the tractor unit is reported in fig.7.4. It is just an arrow shaped tool with tines

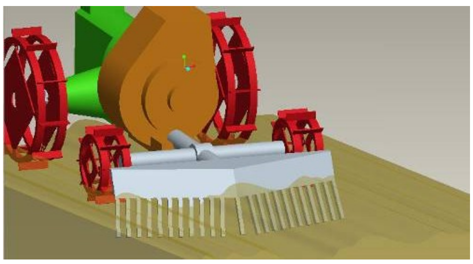


Fig. 7.4. Arrow rake pushing mines beside.

Considering the advantage of some sort of additional movement of the tool, at first I thought about a mechanism for helping soil failure under tool action at the same time as helping mines to move toward soil surface. I thought about adding moving tines to the fixed ones, pushing mines from the button. I chose to use an articulated mechanism (fig.7.5), powered by a belt system conveying rotational movement from the front wheels to the blue wheel. For its synthesis I developed a simple code in MAPLE calculating the movement of the end-effector upon the input of member length values. The model used to derive equations implemented by MAPLE code is in fig.7.6.

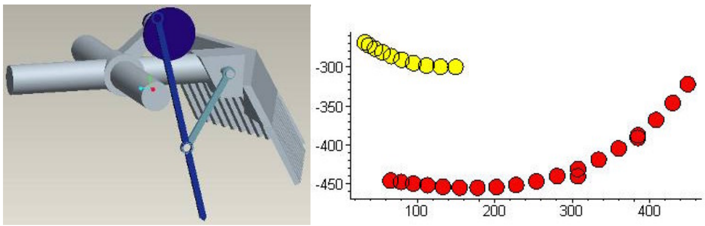
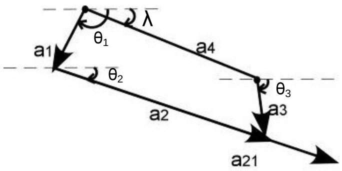


Fig.7.5. Moving rake. Position [mm]/[mm] of articulated mechanism end-effector (red points).



Input: $a_1, a_2, a_3, a_4, \lambda, \theta_1$(motor)

Output: θ_2, θ_3

$$\overline{AB} + \overline{BC} = \overline{AD} + \overline{DC}$$

$$a_1 \cdot \cos\theta_1 + a_2 \cdot \cos\theta_2 - a_3 \cdot \cos\theta_3 - a_4 \cdot \cos\lambda = 0$$

$$a_1 \cdot \sin\theta_1 + a_2 \cdot \sin\theta_2 - a_3 \cdot \sin\theta_3 - a_4 \cdot \sin\lambda = 0$$

Fig.7.6.Moving rake model for developing MAPLE code.

Although only outlined and not implemented in following ground processing tool design versions, specifically designed for soft soil, the idea of a set of moving tines could be exploited further in future design of new tools.

A fixed, arrow shaped, slotted ground processing tool pushed by a prime mover is a system already used in military demining, for breaching a lane in a minefield for quick access of troops. It is designed and sold by Pearson engineering, the same company producing the Pearson minefield tractor (see paragraph 2.3). The prime mover here is a tank, as it is used by military, but the same principle could be scaled and applied to my machine.

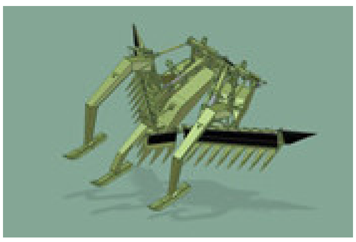


Fig.7.7.Mine plough (source: Pearson Engineering, http://www.pearson-eng.com/products/viewProduct.aspx?id=1&type=m).

7.3. Ground processing tool design

As well as for the tractor unit frame design, also for the ground processing tool design I had the possibility to discuss important choices with Mr. Ross Macmillan, senior academic associate in agricultural engineering at the University of Melbourne who kindly accepted to work with me for one month at the University of Genova.

The final version of the ground processing tool [7.4] embeds two tools: a single blade to cut the soil and tines to sieve soil away and retain mines. It is designed to operate 150mm deep, 50mm more than the depth required by Sri Lankan standard, to lower possibilities to miss mines: in fact, 100mm clearance depth is the excavation depth required to manual deminers, who can dig deeper to remove a landmine that has been exposed to eye sight by previous excavation.

There were three important implications in deciding its final shape.

Weight transfer (fig.7.8): most soil engaging tools involve a horizontal (draft) and vertical force. When the tool is mounted on the front of the tractor both of these forces, together with the weight of the tool, have the effect of transferring weight from the rear to the front of the tractor. These effects are generally undesirable (on a rear wheel drive tractor) and hence it is important that they do not become excessive.

Depth control: the requirement for good depth control is to avoid the tool working too shallow and missing mines or digging too deep and causing the tractor engine to stall or the tracks to slip. Mounting the tool on the tractor alone is likely to cause a variation in depth as the tractor pitches in the vertical longitudinal plane. Therefore I decided to fit a depth wheel running in the undisturbed soil ahead of the tool (fig.7.8). This reduces the weight transfer effect of the tool and assists in depth control. It is in the form of a cage wheel on the assumption that this will suffer minimum damage if a mine were to explode under it.

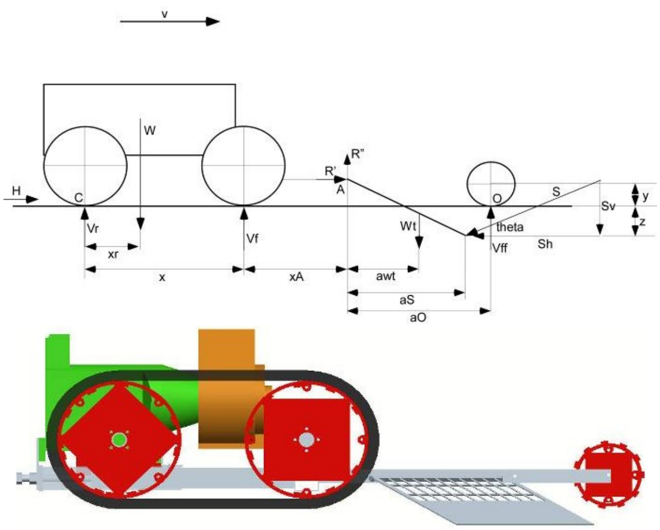


Fig 7.8. Weight transfer model and digital mock up.

Moreover, it is desirable, in the interests of simplicity, that the tool is formed from plane shapes. The simplest form of such a tool is therefore defined by two angles: the rake angle, between the tool and the horizontal (ground) in the longitudinal vertical plane, and a side angle, between the tool and the vertical longitudinal plane in the horizontal plane (fig.7.9).

Different low-fidelity, crap up, prototypes with different rake and side angles were made and tested in a sand bed with the help of Fabio Rossi, a high school student who had a one week stage at my laboratory (fig.7.9).

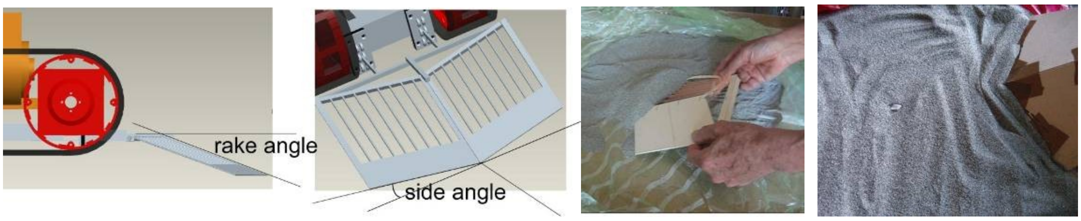


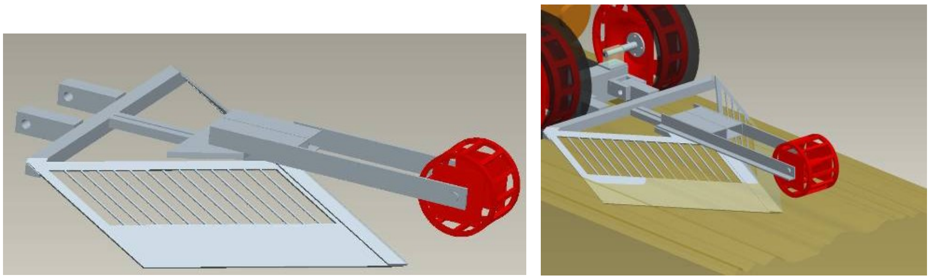
Fig 7.9. Ground processing tool definition angles and low-fidelity prototypes.

Tests showed that a small rake angle allows the soil to flow up the tool in a thin sheet and so encourages sieving, while a small side angle tends to cause the soil to build up in front of the tool and to be moved to the side without being processed. I also noticed that sand in front of the tool tip, included in an angle approximately the same as the angle included by the two side plates of the tool, the complementary of the two side angles, tends not to move, being out of the zone of influence of the tool. Therefore, the smaller the rake angle and the bigger the side angle, the better soil processing is.

To achieve mine disposal sideways, I adopted a side angle equal to 50° and rake angle equal to 30°. The rake angle had to be increased to keep the distance of the tool tip from the tractor unit relatively small.

The success of the tool in sieving soil and retaining or shedding mines depends on the form of the tool described above but also on the form of the sieve. Simplicity suggests that the form of the sieve members should either be in the plane of the sides of the tool, either parallel to the spine of the tool (effectively at the rake angle) or alternatively at the side angle (effectively horizontal). It seemed useful, in evaluative terms, to make one side of the sieve in one form and one in the other (fig.7.10). This would provide an immediate and obvious comparison of the two forms and guide future developments. As the tool will work in Sri Lanka, distance between tines has been set to be less than 38mm, the minimum dimension of the smallest landmines Type72AP and P4-Mk1.

As previously point out, it is understood that some form of active movement of the tool would assist in breaking clods and clumps and so improve the sieving process. This however should not be necessary in sandy soil for which the initial form of tool is being developed. However it is likely to be needed for future prototypes addressing other heavier soils.



Mass properties of the model

m = 110kg

distance between hitch and front axis, xA = 105mm

distance between hitch and centre of gravity, awt = 636mm

distance between hitch and tool tip, aS = 1303mm

distance between hitch and depth control wheel axis, aO = 1460mm

depth control wheel radius, y = 135mm

depth of work, z = 150mm

Fig. 7.10. Ground processing tool final design.

Due to the effect of the depth control wheel, weight transfer is almost not affected. From the model in fig.7.8, using mass properties of the final model of the tractor unit (fig.6.14) and of the final model of the ground processing tool (fig.7.10), considering a soil tool interaction force S = 2500N inclined of 17° with respect to the horizontal (paragraph 7.4), the soil reaction force under rear and front wheels can be calculated as equal to Vr = 1430N, Vf = 3800N, while the soil reaction force under depth control wheel as equal to Vff = 1410N.

7.4. Calculation of soil-tool interaction force and FEM analysis

To calculate the draft force of the ground processing tool designed and compare it with the drawbar pull exerted by the tractor unit, estimated to be more than 3kN (see paragraph 6.2), I used two different empirical models. In fact, the fundamental earth moving equation developed by Reece [7.5] in 1965 gives the implement draft force as sum of four terms, respectively function of soil cohesion, surcharge pressure on failure surface, bulk density and tangential adhesion at soil metal interface. Each one of these forces can be calculated only if some soil parameters and dimensionless factors are measured in the field. Due to the impossibility to measure them in the field, I used a semi empirical approach.

From Agricultural Machinery Management Data, ASAE D497.5 FEB2006, published by the American Society of Agricultural and Biological Engineers (ASABE), the draft force, defined as the force required in the horizontal direction of travel for tools operated at shallow depths is given by eq.7.3.

$$D = \varepsilon \cdot [A + B(v) + C(v)^2] \cdot \tau \cdot z \qquad (7.3)$$

Where, D is the implement draft, ε is a dimensionless soil texture adjustment parameter whose value is given in ASABE tables, A, B and C are machine specific parameters, given in ASABE tables, v is field speed, τ is tool width, z is tillage depth. The value for the draft force necessary to push a tool, considered as 100mm twisted shovel chisel plough, 1000mm wide, at 150mm depth, at 1.1km/h, in fine textured soil, is approximately 2kN.

I obtained a second estimation of the draft force of approximately 2.2kN extrapolating data regarding a 19 tine scarifier fitted with 150mm wide dart points operating at 110mm depth [7.6]. In both cases, draft force of the ground processing tool is less than the drawbar pull exerted by the tractor unit.

A finite element analysis on the ground processing tool showed that steel plates 8mm thick are suitable to be used as plane shapes for the tool. With a horizontal load of 2.5kN applied on the spine and on side plates, the maximum stress induced, calculated with Von Mises criterion on the plates is less than 140MPa, while the maximum displacement is less than 4mm (fig.7.11). Yield strength for steel is 235MPa.

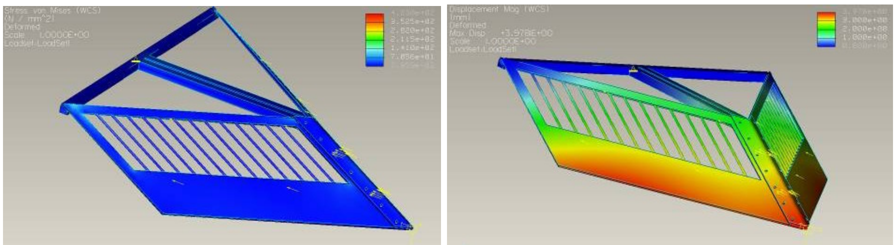


Fig. 7.11. FEM analyses on ground processing tool (steel plates 8mm thick).

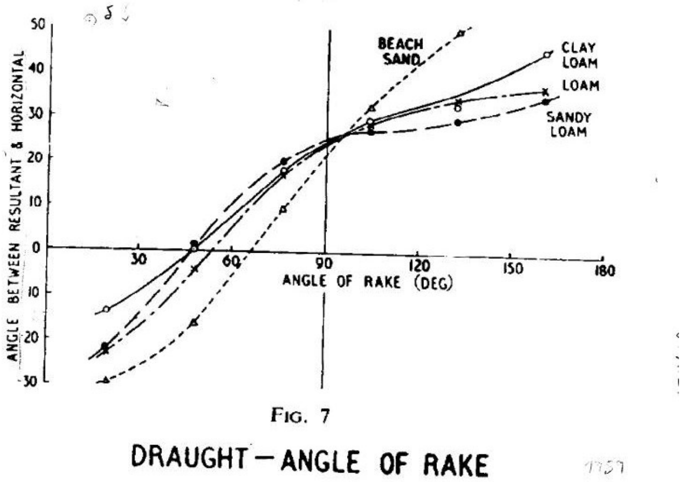


Fig. 7.12. Angle between soil tool interaction force wrt the horizontal Vs rake angle (source: Payne [7.7]).

A work done by Payne and Tanner [7.7] on the effect of tine geometry on soil disturbance gave me the means by estimating the angle of inclination of soil tool interaction force with respect to the horizontal. From the graph in fig.7.12, can be seen that the angle by which the force is inclined with respect to the horizontal depends on the rake angle and for the ground processing tool that has 30° rake angle, the angle between soil tool interaction resultant and horizontal is approximately 17°.

7.5. Ground processing tool manufacturing and test in Jordan

After having developed and tested a first prototype of the tractor unit in Italy, thanks to the kind support of NPA Jordan, the University of Jordan and my co-supervisor Andy Smith, I had the possibility to organize a test of the ground processing tool in realistic minefield conditions in Jordan, in March 2008.

In fact, due to the intensification of civil conflict and the recent decline into a war-like situation in Sri Lanka, I have been suggested by my co-supervisor Andy Smith to test the ground processing tool in Jordan, where NPA has implemented the same excavation system in use in Sri Lanka, based on the use of rakes. Unfortunately, it was impossible to test the ground processing tool and the tractor unit at the same time, as resources and time were not enough either for developing a second prototype of the machine locally or for transporting the Italian prototype in Jordan. Therefore, I set up a system for testing the ground processing tool using standard agricultural equipment available in the country.

Having the possibility to manufacture and test the tool in the field, allowed me to verify two important requirements of the tool: if the design was simple enough for manufacturing in a not specialized workshop in a middle income, developing country and if the concept worked, i.e. if, in realistic field conditions and in the same soil it has been designed for, the ground processing tool worked, by moving landmines to the side and lifting them on soil surface.

The ground processing tool (fig.7.13) was manufactured in the workshop of RAMA Agricultural Equipment in Amman, Jordan, between the 15th and 18th of March. RAMA company kindly accepted to collaborate to the project by providing all material and work for free and is here warmly acknowledged. The ground processing tool produced differs slightly from original drawings. In fact, together with the people working in the workshop, particularly with Yusef Abutimah, Hassan Omar and Ahmed Sabama, we adapted original drawings to the standard profiles available in the workshop, changing dimensions and remaking necessary calculations in real time.

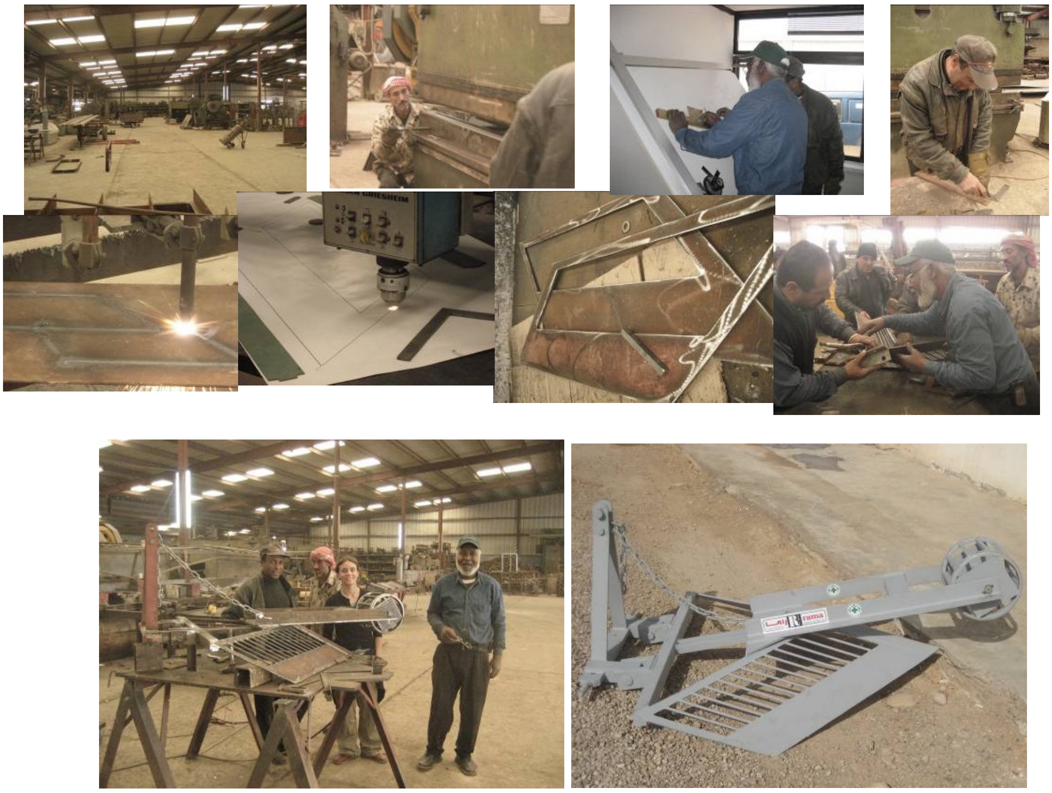


Fig. 7.13. Ground processing tool manufacturing phases and final prototype.

The participation of Yusef, Hassan and Ahmed to the work for adapting the design to the material available, increased progressively during the four days work in the workshop. On the last day, they suggested to abandon the original design (fig.7.14) of the frame connecting the ground processing tool to the three point linkage attachment of the tractor to be used for testing and instead use an existing frame already available in the workshop.

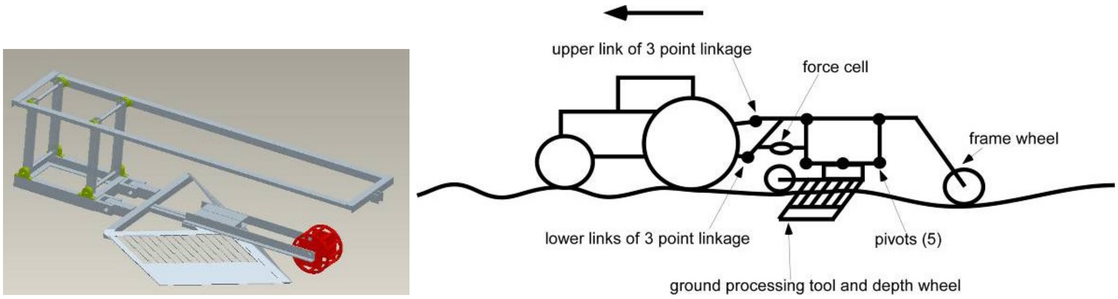


Fig. 7.14. Original design and concept of supporting frame for ground processing tool during test.

The frame originally designed allowed sensors to be embedded and vibration to be added to the tool in possible future tests, but it was much more complex and longer to manufacture. Therefore, I decided to abandon it and readapt the existing frame as suggested by Yusef, Hassan and Ahmed (fig.7.15).

Fig. 7.15. Hassan, Yusef and Ahmed working at the supporting frame, and frame prototype.

The frame can be attached to any tractor presenting category I three point linkage attachment. In this way, any small tractor can be used as prime mover, with the ground processing tool attached to the frame. As usually the ground processing tool would be pushed in front of the tractor unit, while in tractors the three point linkage attachment is at the back, during test the tractor was driven backwards (fig.7.16). The ground processing tool is rigidly connected to the depth control wheel and is pivoted to the frame allowing it to follow ground profile. The chain connecting the upper linkage to the ground processing tool is used only during transport of the tool for lifting it from soil. During work, the chain is loose.

The same system (tractor driven backwards plus three point frame for supporting the tool) can be used for testing other new tools derived from future design iterations.

Fig. 7.16. Testing system (tractor driven backwards plus three point frame for supporting the tool) and use of chain.

The list of all parts and relative technical drawings and dimensions of the frame are reported in appendix II. The changes made to them during manufacturing at RAMA workshop are also reported in appendix II. The tool was produced within 4 days of work.

The ground processing tool and frame can be transported at the back of a pickup (1.4m x1.4m) with the front wheel slightly sticking out, as the overall width is approximately 1,2m and the length including the front wheel is 1,5m. The weight of tool and frame is 125kg.

7.6. Ground processing tool field test

Test took place in Ar-Risha, near to Aqaba, in the South of Jordan at the boarder with Israel, under the supervision of NPA, in an area free from active landmines, but near to minefields (Wadi Araba minefields, fig.7.17) and therefore presenting similar characteristics.

During tests I received precious support from Jochen Kuhm, working for Minewolf Systems, a company producing machine for humanitarian demining, who kindly accepted to help me on a day off from his work on the Minewolf machine.

I chose two sites as test locations: sandy soil (site A), sandy soil with crust (site B) and sandy soil with stones (site C). Characteristics of the soil of these sites are reported in paragraph 7.6.1.

I laid landmines in test lanes 1m wide by 10m long, at intervals of 1m along the lane length, in different position with respect to the middle line of the lane to see their different translocation in relation to their different original position at the tool passage. The scheme representing test lanes is reported in paragraph 7.6.1. Real mines could not be used as the prime mover of the ground processing tool was a small tractor category I (40hp) hired locally from a deminer. For connecting the ground processing tool to the tractor I used the frame developed at RAMA workshop, attached to the three point linkage hitch at the back of the tractor (fig.7.18).

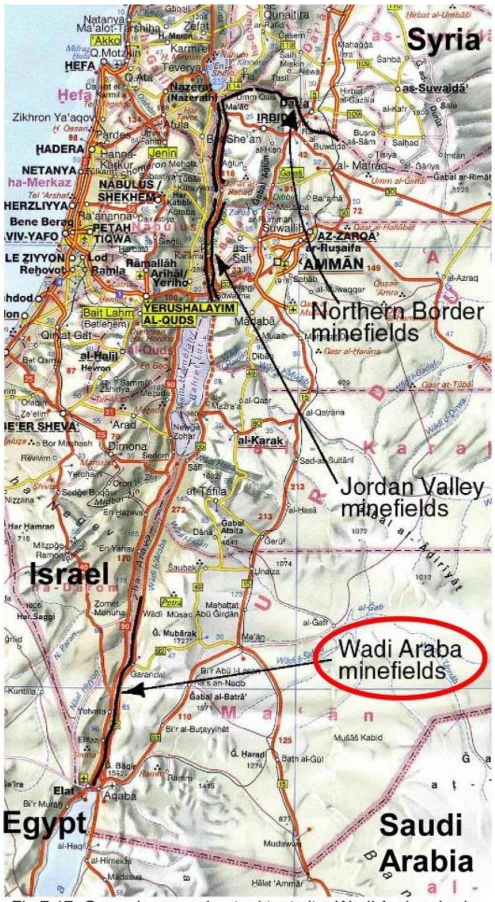


Fig.7.17. Ground processing tool test site. Wadi Araba, Jordan.

Results [7.8] were promising. The tool shape seems satisfying as soil and landmines contained in it is processed according to what was desired: the tool lifts lift mines on soil surface and push them side ways. Therefore the side angle (50°) and rake angle (30°) chosen work well. Soil is lifted and moved to the side of the tool while sifted by side blades (fig.7.18).

Fig. 7.18. Soil processed by the ground processing tool. A landmine pushed to the side can be seen (green).

Soil translocation didn't happen in test site C, sand with small stones, as the tool didn't even enter the ground, too hard to be scarified by the tool tip. This is not worrying as the soil was too hard also to be excavated with the hard rake usually used by deminers; therefore it is not a soil the ground processing tool is designed for.

The good soil translocation by the tool could be noticed even if a proper test in the prepared 10m lane could not take place. In fact, soil translocated and loosened by the tool built up on the sides of the tool, as it was desired, but due to the particular dimensions of tractor available and used as prime mover, tractor wheels passed right over the loosened soil (fig.7.19). As the tool moved forward, more soil was left on the side and wheels started spinning. After a short period of time, the machine stopped providing the sufficient traction and could not proceed any more. The wrong match between the tool and the tractor width is due to the fact that the tool is designed for the tractor unit and not for the tractor, which is slightly larger. At the time I designed the tool, in Italy, and until I didn't go to the field in Ar-Risha and found a tractor to hire, I didn't known which tractor would have been available. A wider tractor, category II or category III could be successfully employed in testing, but it was not available in Ar Risha at the time I was there.

When I was in the field I tried different approaches (fig.7.19) to solve the problem of low traction on loosened soil. But, neither locking the differential and increasing weight on wheels, nor lowering air in tires was effective and the problem persisted.

Fig. 7.19. Soil processed by the ground processing tool moved right under tractor wheels. Adding weight on wheel axis (pink bags) and decreasing tire pressure.

Definitely for future test of this or different tools, a different prime mover has to be used; the same could be employed if chains or tracks are available. If the same tractor is going to be used, as it is easily available, a wider and bigger tool has to be manufactured that matches with tractor width. Considerations to take into account for this second possible design iteration regards also the possibility to add vertical tines on top of side blades to process the soil that accumulates on top of blades after some time soil processing starts. This would impede soil and landmines contained in it to skip the sifting grid and fall into the lane where the machine passes (fig.7.20).

The front wheel has to be different depending on the soil processed: open cage wheel is good for sandy soil with crust but fails in pure sand. Here a pneumatic tire would be more suitable.
Details of test preparation and results are reported hereafter.

Fig. 7.20. Soil processed built up on the tool and front wheel sinking in pure sand.

After the test, discussing with Jochen, it seemed a good idea to take into account in the design next version of ground processing tool, to make side blades thicker. This suggestion comes from Johen experience with Minewolf machine working in sandy environment for months: on long term sand acts as abrasive material and consumes steel.

7.6.1. Test preparation

Test site details are reported in fig.7.22, fig.7.23 and fig.7.24. To measure soil characteristics I used a penetrometer (fig.7.21) kindly lent by the University of Jordan. It is constituted by a spring on which force is applied by acting on the handler; different heads with different sizes can be screwed on the penetrometer tip, making it possible to measure the pressure a large variety of soils can bear. The force applied to the handler can be read on the handler itself, where tags are positioned. Tags do not correspond to mm and therefore I was not able to state the units of the spring constant. From a table given to me by the university, I could only calculate the value of the constant k as equal to 4,310. Therefore, for obtaining pressures in MPa soils of sites A, B and C can bear I used eq.7.4, where k is the spring constant, R is the distance read on penetrometer handler and D is the diameter of the head in mm. When the bigger head could not penetrate the soil any more, I mounted a smaller one.

$$p = \frac{k \cdot R \cdot 4}{\pi \cdot D^2} \quad (7.4)$$

Fig. 7.21. Penetrometer measurement.

Test site A: sandy soil

Penetrometer head size D/mm	Penetration depth Tag n°/mm	Reading R/MPa
D3/20.5mm	8/100mm	94/1.2MPa
D7cone/base diameter=6mm	All	78/11.9MPa

Fig. 7.22. Test site A, characteristics.

Test site B: sandy soil with crust

Penetrometer head size D/mm	Penetration depth Tag n°/mm	Reading R/MPa
D5/13mm	8/100mm	58/2MPa
D7cone/base diameter=6mm	All	84/12.8MPa

Fig. 7.23. Test site B, characteristics.

Test site C: sandy with small stones

Penetrometer head size D/mm	Penetration depth Tag n°/mm	Reading R/MPa
D7cone/base diameter=6mm	All	86/13MPa

Fig. 7.24. Test site C, characteristics.

I prepared test lanes, burying 11 wooden landmines, M35 type, according to the scheme in fig.7.25. Wooden landmines were kindly provided by NPA, who usually use them for deminers training. Characteristics are reported in fig.7.25.

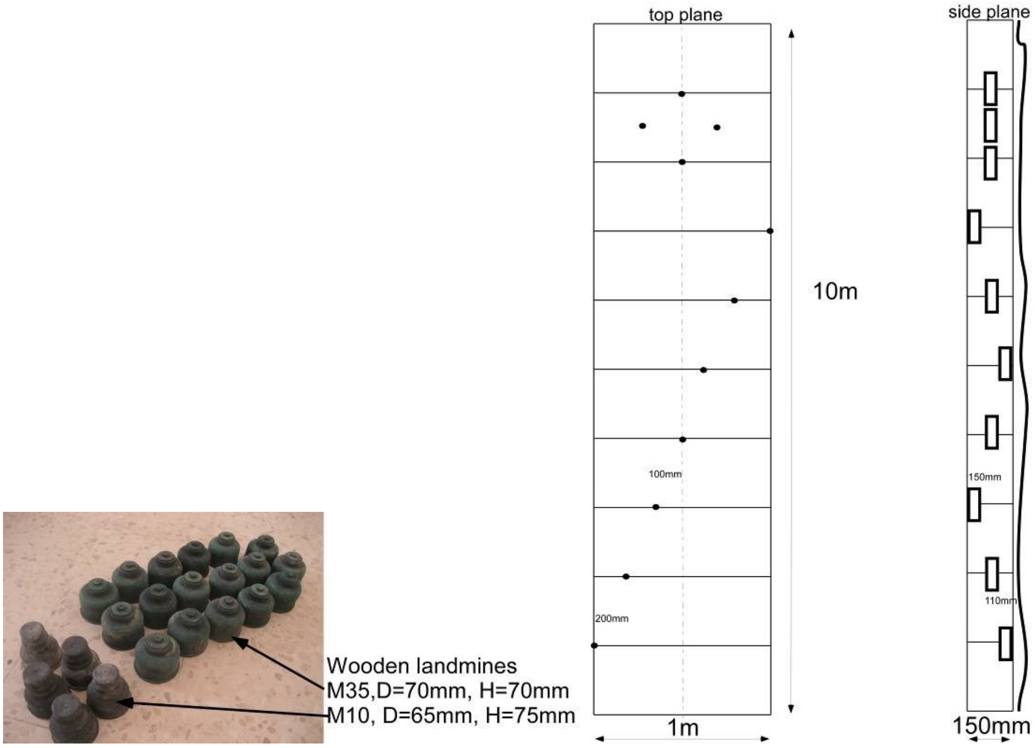
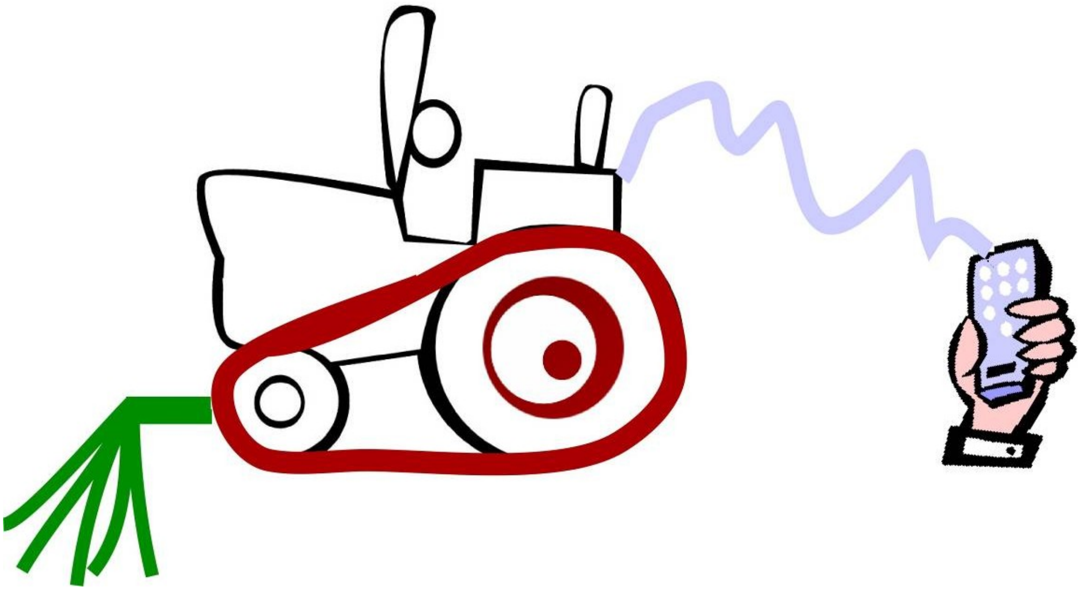


Fig. 7.25. Wooden landmines and their deployment in test lane .

I also prepared forms to fill in with results obtained from tests. The landmine movements I recorded were on three planes. On top plane the distance from original location, on side plane the distance from soil surface and on landmine top plane the position of the pressure plate, up or down.

Chapter 8 Control



- Implementation of control with IMRob students
- Control unit
- Assembly and instruction manual
- Test under no load

8.1. Implementation of control with IMRob students

The control system [8.1] could be implemented also thanks to the help of three students of the International Master in Robotics (IMRob), held in 2007 at my department. As final project of their master, Szymon Kostrzewski, Rusiru Dasantha Apputhanthri and Jawaad Masood designed and implemented practically a first version of the control system on the powertiller; I supervised their project.

Therefore, here I treated their work [8.2] only briefly, just enough to give a general understanding of it and, as this thesis aims to be also a reference for the eventual users of the machine, in paragraph 8.3 I outlined a user manual explaining how to operate the machine. References for maintenance of the control system as well as for possible upgrading can be found in Appendix III, containing the list of all components chosen, the software code and electric circuit diagrams and pictures.

During the work on the ground processing tool, the advantages of having a vibratory tool instead of a fixed one to operate in harder soil became clear. A further cylinder to propel the tool back and forward could be added, as there are both enough pressure and ports on the PLC. Data reported in Appendix III would be essential for this upgrade.

8.2. Control unit

The portable control unit allows controlling the machine from remote distance. The module allows forward motion by acting on the clutch, differential and acceleration of the power tiller; steering is controlled by additional brakes, mounted on the driving axle (paragraph 6.2). The module can be fit to every kind of power tiller actuated by levers, using differential gear, after only little adjustments. Components choice might vary, according to needs and to the power of the powertiller chosen. Anyhow, scaling of the system should be easily made by recalculating brake force requirements described in paragraph 6.1 and forces necessary to actuate levers; bore diameters of new cylinders are given by eq.6.26, considering a pressure of 6bar (= 0.6MPa), the operating pressure of the compressed air of the control system. Due to its portability the control unit is treated as a different module. The unit, like the other modules, responds to the requirements of safety, low-cost and *simpleffectiveness*. Actuation is pneumatic.

According to previous considerations (paragraph 6.1), the features selected for actuation are shown in fig.8.1. and fig.8.2.

Feature	Motion type	Actuator type
Differential	Angular and linear; linear easier to apply; deadlocks during switching the differential on	Single-acting cylinder, return stroke by spring
Clutch	Linear motion, big force, no deadlocks, one-side force needed	Single-acting cylinder, return stroke by spring
Acceleration	Linear motion, low force, position holding	Double-acting cylinder
L / R brake	Linear motion, one-side force, no deadlocks	Single-acting cylinder, return stroke by spring

Fig.8.1. Tractor unit features actuated by control system.

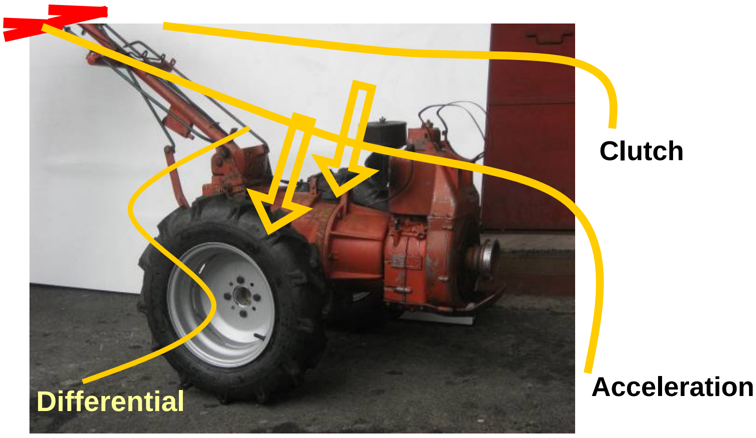


Fig.8.2. Tractor unit features actuated by control system, scheme.

Only the minimum number of levers is actuated remotely. This allows a simpler and cheaper system to be on the machine to the detriment of more manual work and less variability of operational mode. In fact, with the control system implemented, the operator has to manually start the machine, as the powertiller is very old there is no electric starting system and the engine starts by pulling a rope rolled on the engine shaft, select the gear and insert forward motion. The powertiller starts moving when clutch is released by acting on the control.

The analysis of type of motion required to actuate features (fig.8.1) showed that actuators providing linear motion could be used for all commands. In some cases actuation is needed in both movement directions in others one direction is passive. The presence of deadlocks in differential gear, particularly significant for the old powertiller we employed, was taken into consideration in choosing the type of actuation for control system.

Control system actuation is pneumatic, but it could also be realized electrically or hydraulically. The choice of a pneumatic system was taken after the analysis of advantages and drawbacks of all three possible systems. The advantages of electric control are the large availability of parts, the possibility to achieve precise positioning when external sensors are added, easy assembly, the resistance to shock and low cost of commonly used parts. Drawbacks include the need of a micro chip circuit board for remote control, difficult realization of linear motion and not easy overcoming of deadlocks, and low resistance to vibrations and contaminations of the actuators. For the hydraulic control, advantages are the possibility to have slow motions and big forces, to achieve both angular and linear motion, good resistance to vibrations and contamination and the biggest available power-mass ratio. While drawbacks include the high cost of pumps, valves and actuators, the need of additional equipment such as the pump and oil accumulator and the need of many oil hoses that can be easily damaged. Instead, the pneumatic system is characterized by providing natural linear motion, through cylinders, is resistant to deadlocks and to vibrations and contamination, there is a big variety of actuators available and it can be integrated with hydraulic system (disc brake system using penumo-hydraulic amplifiers). While electric system needs power generator and hydraulic one needs a pump, the pneumatic system needs an air-compressor.

Actuators chosen are pneumatic cylinders. The list of cylinders and solenoid valves purchased and mounted on the powertiller is reported in appendix III.I, while in fig.8.3 forces and cylinders displacements required to actuate levers are reported. Brakes are treated in paragraph 6.1.

Feature	**Motion**	**Force [N]**	**Displacement [mm]**
Differential	Linear	100	20
Acceleration	Linear	20	12
Clutch	Linear	1200	11

Fig.8.3. Tractor unit features: cylinder forces and displacements.

Control system was designed accordingly to digital control system design Moore approach. Logic equations, determining actuators movements, could be implemented in different ways: as relay circuit (ladder diagram), digital logic circuit (using available electronic stuff), microchip program or an off the shelf programmable logic controller (PLC). For this application it was chosen to employ the Siemens Logo! PLC which is cheap and robust, allows for software based programming, doesn't need conventional switches and extended communication features can be used. This selection fulfilled requirements as well as allowed for future extensions.

By now, the control is via umbilical, not radio. Therefore, power supply both electrical and pneumatic as well as control signals, from the remote control panel, arrive to the machine through cables (fig.8.4). Radio control could be implemented easily in the future: an air compressor to be fit on the machine and powered by the same engine shaft that is used for starting has been chosen (see appendix III.III) and space on the tractor unit to host it, has been allocated (see the grey box in front of the engine in fig.8.5); the design of radio control transmitter and receiver has still to be done and a battery should also be selected and added on board.

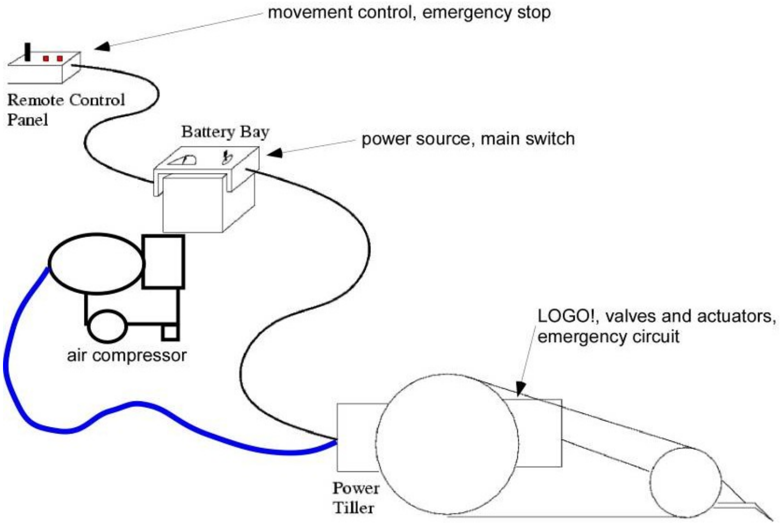


Fig.8.4. General control system scheme.

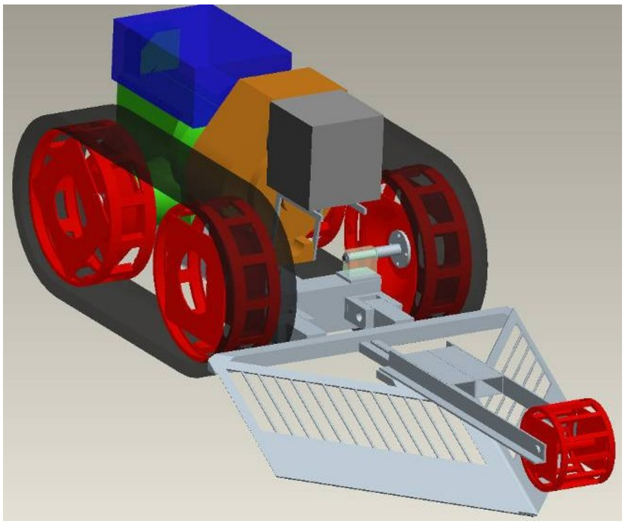


Fig.8.5. Air compressor (grey box) and valve bay (blue box) mounted on the machine model.

Operating the machine in the laboratory via umbilical allowed us to use a battery and an air compressor not dedicated to the task. With umbilical the maximum control distance is mainly limited by the length of wires and tubes.

8.3. Assembly and instruction manual

Together with master students, we assembled the control system on the powertiller in April 2007, before their final project presentation.

The remote control panel (fig.8.6) has four buttons and one lever. The two small black buttons are for right and left turn, the red small button is for braking while the big one, a mushroom button, is for emergency stop. The lever controls acceleration.

Fig.8.6. Machine remote control panel.

By pushing buttons and levers on the remote control panel (appendix III.IV), the operator sends signals to the valve bay on the powertiller, where the Logo! Controller, the electric circuit board and solenoid valves are (fig.8.7) (appendix III.V and III.VI). A big white cable brings signals from the panel to the valve bay. The valve bay also receives compressed air through a tube and electric power, necessary for alimenting the controller from the battery, through two small electric wires. From the valve bay tubes brining compressed air to the actuators exit. Pneumatic cylinders are positioned on the powertiller chassis, near to the features they actuate. Sensors assessing cylinder stroke positions are mounted on the clutch, differential and acceleration cylinders.

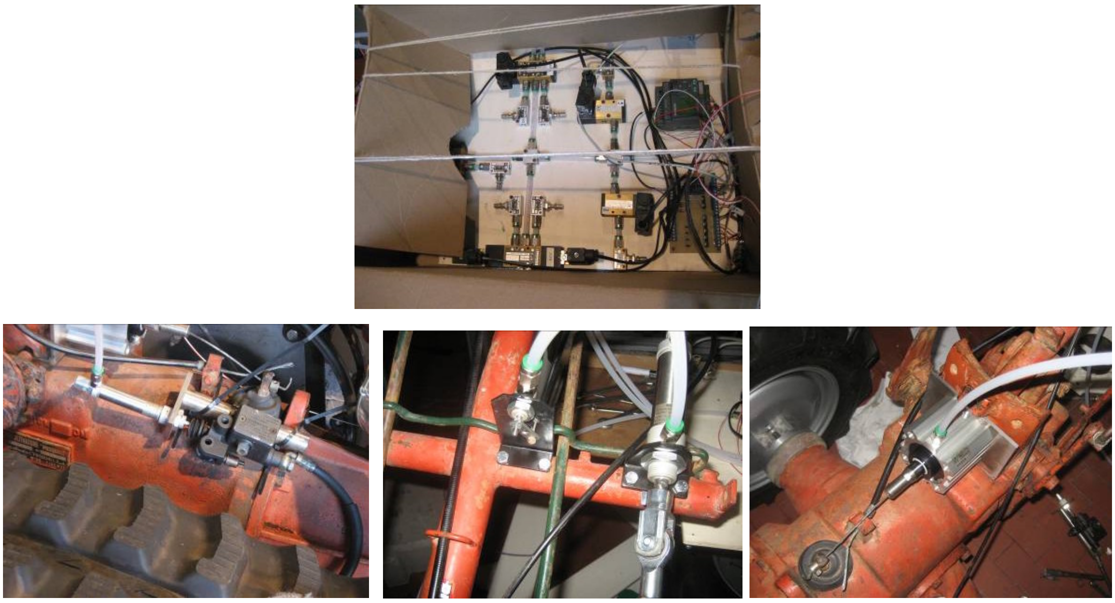


Fig.8.7. Valve bay (provisional box) and fixtures for brakes, acceleration, differential and clutch.

Currently, the valve bay is positioned in a cardboard box. This is only a provisional arrangement; a smaller plastic box should replace the existing one in the future. In this provisional arrangement of the valve bay also includes the main switch of the control system, actuated by a key. Usually, this switch should be on the battery bay, near to the operator at the border of the minefield (fig.8.3). Therefore, usually, only the big white cable and the air tube should enter the valve bay.

Electric power is brought to the controller by the white cable coming out from the battery bay, bringing control signals as well as power supply (appendix III.VII). This cable, exiting the key switch contact panel and entering the valve bay electric circuit board, is now inside the valve bay, under the wooden board. Now, electric power is brought to the valve bay by two small electric cables directly connected to an external battery.

Air is compressed by an external air compressor, positioned near to the operator. It is brought to solenoid valves positioned in the valve bay by a tube. Near to the valve bay, on the powertiller handler is positioned an air pressure regulator with filter (fig.8.8). The tube coming from the air compressor enters the regulator. Air is driven from the regulator to a single entrance on the valve bay, distributing it to all valves. The system works at a pressure of 6bar, which has to be set by acting on the regulator.

Fig.8.8. Pressure regulator and filter.

The control system is working when the following operations are done.

1. turn the key into the battery bay to ON position (key horizontal, in line with cable connections)
2. connect the battery to the valve bay and switch it on; the controller is switched on and light appears on the screen.
3. connect the air supply, assess all tubes are properly inserted. Open the main air tap, regulate pressure to 6bar, by rotating regulator gear.

To start driving the powertiller, it is necessary to manually start the engine first. Unfortunately, the only way to start it is by pulling a rope previously rounded on the engine shaft. This requires good practice and a great force, I personally cannot exert. A trick to start the engine with fewer trials is to heat the air entering the filter before pulling. The rope should be rounded around the shaft, previously turned manually until the compression point of the cylinder is reached (turning becomes harder), only two or three times. The engine has to be started with the air inlet under the filter closed, this must be opened as soon as the engine starts. In case of cold weather, it might be necessary to push a button near the carburettor, pumping fuel up.

The engine has to be started in neutral gear. Anyhow, the shaft doesn't turn if any other gear is inserted.

Before starting the engine is better to check in which direction the powertiller will move. There is a lever (lever C in fig.6.2) on the powertiller handler deciding the direction of motion. To have forward motion, it has to be pushed backwards, toward the handler as shown in fig.8.9.

Before starting the engine, acceleration should be regulated by control to be half way.

Once the control system is switched on and the engine has started to have motion it is necessary to insert the first gear. This is done by pushing the gear lever D (fig.8.9) one position further than shown in the picture, while pushing the stop button on the control. The stop button actuates the clutch and allows the gear to be inserted. All components have been dimensioned to operate the powertiller in first gear. The maximum speed the machine can achieve in this gear is 0,3m/s, much more than the speed manual deminers can work, so there is no need to change gear or to start motion in other gears.

Fig.8.9. Powertiller levers. D is for changing gears, C for choosing direction of motion .

Once the powertiller has started moving, it is possible to manoeuvre it by acting on the control. Pushing right or left brake buttons, cause the differential to be unlocked and right or left brake to be applied. When the button is released the brake is turned off and differential is locked. When stop button is pushed, the clutch is pulled and both brakes are applied. When the stop button is released brakes turn off and clutch is released. When the acceleration lever is pushed up, acceleration increases at constant speed; when the accelerator lever is pushed down acceleration decreases at constant speed. The accelerator electric circuit is reported in appendix

III. VIII. When the emergency stop button is pushed the spark plug is disconnected from the magnet causing the engine to stop.

8.4. Test under no load

During test organized in occasion of the master students' final project presentation (fig.8.10) the control system proved to work well, all actuators worked at right time, in the right sequence, meaning that the system is well designed. Forces developed by actuators were also enough for actuating and deactivating the differential, the accelerometer and the clutch.

Fig.8.10. Szymon, Rusiru and Jawaa testing the control system during their master final project presentation .

The control system implemented has no capability of steering the machine, as cylinders actuating brakes have been dimensioned only for stopping it. New bigger and more powerful cylinders should be chosen and substituted to brake cylinders in use now, once more details on tractor unit and ground processing tool will be available. Tests with sensors capable of assessing drawbar pull of the tractor unit and soil tool interaction force of ground processing tool should be performed to choose proper braking cylinder dimensions. Nevertheless, all connections, logic equations and necessary button commands on the control panel allowing steering are already implemented in the existing control system and they could be tested under no load, i.e. powertiller not moving.

Chapter 9 Conclusions and future work

9.1. Conclusions and future work

As always happens, trying to fulfil my original ambitious plan is really demanding. And, as always happens, getting close to them makes me really happy. This time even more, as the work I committed myself to do, developing a functioning machine that could be fielded in three years time, involved the practical realization of physical prototypes.

It is with a mix of satisfaction and gratitude to all the people I have met during this long work, who made the physical implementation of this project really possible, that I'm presenting the results and the work that could be done in the future.

The project aimed at two targets, defining a new methodology for designing technology in a participatory way together with end-users and people from the field (the snail system) and applying it to the development of a modular machine for assisting manual demining operations in Sri Lanka.

I used the snail system along the implementation of four work packages, which led to the set up of the implementation plan, the tractor unit first design, the tractor unit re-design, the ground processing tool design and the control unit development. The snail system worked well, allowing me to involve many different stakeholders into the project, from deminers to people working at the GICHD, passing through blacksmiths, mine action technical advisors, people selling components I used, students, researchers and professors, and to integrate their contributions, incredibly valuable as coming from a life long experience in a specific field, into the design of a very simple and low-cost system, whose overall prototypization cost less than 5000€ (appendix IV).

Unfortunately, due to the intensification of Sri Lankan civil conflict that exploded in full scale war in January 2008, the snail system allowed me to exploit participation of other stakeholders more than deminers and other people working in the field. In fact, after the first field visit during which I could do the needs assessment I could not go back to Sri Lanka. Although I devised other systems, not needing face to face communication, for involving deminers and people from the field in Sri Lanka into following design steps, and I integrated them into the snail system, using collaborative tools on the project website, they turned out to be not as powerful as direct communication. The lack of interaction might be due to the slightly time consuming procedure to add modifications or comments and probably moreover to the lack of active involvement of website visitors. A demonstration on how to use it, which was impossible for me to do in this case, in the future should be done in the field, to make end-users familiar to the system.

The modular system developed is composed by a tractor unit, a control unit and a ground processing tool. The tractor unit is the core module, being a platform for supporting other tools that could be needed to assist demining operations as well as the ground processing tool. It is designed around a very old powertiller (from 1944) and therefore would better fit a newer one, with less problems such as deadlocks in gears, responds to requirements of simpleffectiveness,

low cost, and small size: weight and dimensions are so that it can be transported at the back of the small track deminers use to go to the minefield. After several design iterations, the design was simple enough to make it suitable for manufacturing in an unspecialised carpenter workshop.
The control unit has been implemented together with master students and is now functioning on the tractor unit. Few assumptions have been made to make it possible for master student to practically implement it in the time allowed for their final project: in future modifications should be done, most importantly on the external brakes; at the moment they are dimensioned only to stop the machine, they are not capable of turning. New bigger cylinders should be chosen by following steps described in paragraph 6.2 to allow steering remotely.
The ground processing tool prototype is now with NPA Jordan; it was manufactured in a local workshop with the great participation of local workers. Its design is also very simple: the time needed to modify technical drawings to suit material already available in the workshop and to manufacture it, was only four days. During its design and development, the possible use of agricultural derived tools in mine action has been looked with interest by many people. The need of a similar agricultural derived tool to be attached to an existing machine already working in the country has been expressed by NPA Jordan for verification.
The work that could be done in the future is a lot and is open to everybody who would like to contribute through the project website (http://www.dimec.unige.it/PMAR/demining/index.html). There, all design steps are commented and technical drawings are available.
Next steps should involve the integration of prototypes and a structured final test. Results of this test should be the assessment of machine features in quantitative terms, such as drawbar pull capability, slippage, clearing capacity, power consumptions and everything else. For testing the ground processing tool the test preparation described in chapter 8 could be used.
A second iteration of the overall work would certainly improve the design and would be hopefully possible in Jordan, under an agreement between the university of Genova and the university of Jordan, signed during my last visit. It would be very important to be able to test in realistic minefield conditions both the tractor unit and the ground processing tool.
If the design will be used and new machines will be built in different countries, adaptation of the design to local resources will always be needed and should be done in a participatory way together with end-users.

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