Deploying Field Robots for Humanitarian Demining: Challenges, Requirements and Research Trends

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In the aftermath of a war, the existence of buried landmines poses special threats for the local population and human deminers. Although the problem is arguably getting worse, there is a strong potential for robotic solutions to tackle it. In this paper, we outline the challenges involved in humanitarian demining and the technologies currently used in the field. Based on this, we discuss the requirements for proper robotized solutions and overview the effort that has been made by the research community and the trends that have emerged.

Keywords: Humanitarian Demining; Mine Detection; Challenges; Service Robots; Research Trends

1. Introduction

In post-conflict operations, the *demining* process is fundamental to secure civilian resettlement and restore war hit societies. However, guaranteeing that entire land areas are free of mines is very challenging. According to [1–3], around 100 millions landmines are embedded across 84 countries. These mines kill and injure over 20,000 people every year. It is estimated that it would take over 100 years to entirely clear the planet if no other mines were planted in the meantime. Demining lasts 100 times longer than

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Fig. 1. a) A small anti-personnel (AP) mine primarily designed to wound people; b) An anti-tank (AT) mine, typically laid where enemy vehicles are expected to travel.

setting mines and costs in average 300 times more. Also, it is exceedingly dangerous and an accident typically happens for every 2000 mines removed.

Therefore, the removal of landmines has become a global emergency. For this reason, the United Nations has made an effort to draw attention to this problem by proposing the Ottawa Treaty in 1997, which aims at ceasing the production and development of anti-personnel (AP) mines as well as destroying existent stockpiles in signatory nations. However, as of now 35 nations still have not signed the treaty, including USA, Russia, China, Myanmar, India, Israel and Iran.

Battlefield debris like landmines and other unexploded ordnance (UXO) may remain active for decades [4], posing an eminent risk for local people. In addition, they hamper peace-keeping, stability and reconstruction efforts, preventing the recovery of nations, inhibiting the use of land for food production, and not allowing refugees to return home [5]. Thus, the medical, social, economic and environmental consequences are immeasurable [6,7].

There have been important advances related with technology for mine detection and removal, and clearly Science can help the world become a safer place to live. More particularly, robots have the potential to speed up demining and increase its reliability and safety [2]. In the remaining of this article, we further address the problem by identifying the main challenges involved in humanitarian demining and the commonly used technologies in the field. Moreover, the requirements for deploying robot solutions in demining missions are analyzed, as well as research trends in this area. Finally, the article ends with concluding considerations.

2. Humanitarian Demining Challenges

There are two types of mine detection and removal: Military (or Tactical) and Humanitarian (or Post-Conflict) Demining [6]. The former focuses on quickly breaching the field in order to create safe paths for troops under all conditions (*e.g.*, under fire, at the risk of ambush, etc.), while the latter requires complete removal of all mines buried in the field so that the land can be returned to the local population. Humanitarian Demining, which is mainly addressed in this article, comprises three phases [5]: *i) Minefield detection*, usually resorting to war documents or aerial surveillance; *ii) Mechanized detonation* using armored machinery; and *iii) Manual inspection* to insure 100% of clearance efficiency.

Humanitarian demining poses several issues. It is typically a problem of poor countries dispossessed of basic infrastructure and without access to costly demining equipment. There are about 2000 types of mines with different initiators, detonators, penetrators, explosive loads and metallic content, which leads to time, labor and fund wasting due to false positive detections [2,3,6,8]. Moreover, it involves diverse environmental conditions, including different climates, density of vegetation and types of soil. According to [9], the Cambodian Mine Action Centre (CMAC) reported that vegetation removal was responsible for 70% of the time spend on landmine clearance, due to its variability, the existence of trip-wires and risk of poisonous snakes and mosquito-borne diseases by human operators.

Nowadays, several minimal metal mines are still produced and metal is being progressively replaced by plastic and wood to hinder mine detection systems. Landmines are commonly hard to reach: it is necessary to progressively apply an adequate force for excavation until reaching the required depth for inspection [3], and several sources can trigger a landmine such as pressure, movement, sound, magnetism and vibration. On the upside, AP mines (*cf.* Fig. 1) are commonly found at shallow depths to guarantee detonation, however they can move deeper due to heavy rains [2], making them much harder to detect. In such changeable environment, finding reliable and adequate solutions is complex.

3. Technologies for Mine Detection

Developing and testing new technologies for demining is a vital process. The most used sensor technology are metal detectors (MDs), which are based on the principle of electromagnetic induction. MDs have been enhanced over the years to enable background rejection so as to avoid false alarms due to metal fragments. They usually have small dimensions, low weight, low energy consumption and low cost. However, they still suffer from limitations related to the magnetic properties of the soil, concentration of metal scraps, burial depth of mines and mines with minimal metal composition.

Furthermore, advances in geophysical technologies have enabled the utilization of subsurface imaging. Particularly, Ground Penetrating Radars (GPRs) have been employed in the field with promising results [10]. This technology is useful for the discrimination of targets, enabling the visualization of their shape [8] up to 30 cm of depth, albeit their sensitiveness to heterogeneous soil moisture. GPR works by emitting an electromagnetic wave into the ground using an antenna which does not need direct ground contact. In order to overcome the limitations of MDs and GPR, and explore their complementary features, it is also common to combine both sensors in a *dual* configuration. Such solutions require methods for data fusion and are commonly employed in a hand-held device or vehicle, *e.g.* [11,12].

Another prominent alternative are vapor explosive detection systems, which have been emerging with the increasing knowledge on how sniffing dogs discover explosives. Vapor detection techniques aim to study and develop techniques based on chemical sensors to assess the migration of explosives, vapor leaking from mines and possibly other odors. Several other technologies have emerged with different levels of technological maturity, such as passive microwave radiometers, thermal, multi-spectral and acoustic imaging systems, photo-acoustic spectroscopy, X-ray backscatter techniques, nuclear quadropole resonance (NQR), thermal and fast neutron analysis (TNA & FNA), multi-sensor probes with force and tactile feedback, and others. For additional details on emerging sensing technologies for mine detection the reader should refer to [6,10].

4. Robotized Solutions

Despite the development of diverse detection methods, humanitarian demining often relies on trained sniffer dogs and manual clearance by hand prodding, which is slow, tedious, stressful and dangerous for human operators [2–7]. Clearly, robotic technology advancements may play an important role in this context, improving operational performance and safety by distancing personnel from the threat. As a robotic application, mine clearance and removal is challenging and risky, however it has tremendous potential.

4.1. *Requirements*

Development in robotic technology offers prospects to address demining applications, still there are several requirements that need to be addressed. Besides increasing safety for human deminers, robotic systems should increase productivity by speeding up the process. Also, such systems must generate minimal false positives by distinguishing landmines from other buried debris, while being sensitive to all possible types of explosive devices. Additionally, they should be able to operate and maneuver for long periods of time in varied environments and terrains over wide areas. Hereupon, robustness against vibration and mechanical shocks plays an important role, as well as easiness of maintenance, operation and field deployment, since these equipment will mainly be used in third-world countries. For the same reason, they should be affordable and cost-effective, making use of off-the-shelf components and matured technology [2,4,6].

Mechanisms for self-recovery during navigation and mine searching are highly desirable, as well as intuitive human-machine interfaces with real-time interaction, where mines are precisely marked, located and discriminated. This can be made possible by including high-distance wireless communication links in these platforms, vegetation cutters, and compact, portable, fast-response and reliable mine detecting systems [13]. For this purpose, the platform should have a modular, flexible and reliable design, assuring adequate balance between maneuverability, stability, speed and the ability to overcome obstacles [2]. Moreover, it should exert low ground pressure and the sensitive parts of the robot, which may be difficult to replace, should be well protected in order to withstand explosive blasts [3].

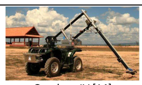
Robots should function in distinct operational modes, such as remotely controlled, semi-autonomous and autonomous modes. This implies several capabilities like intelligent planning, high mobility in unstructured terrains, environment perception and mapping, coupled with signal processing and data fusion techniques to deal with the integration of different sensors [2], while minimizing the noise implied in detection devices [14].

4.2. *Field Research Robots*

Existing solutions are highly diversified, ranging from all-terrain vehicles to multi-legged platforms and even suspended pole robots [7]. These robots are endowed with different locomotion concepts in order to adapt to unstructured environments. Terrain assessment and modeling is fundamental, since field conditions may limit the progress of demining missions [14]. Thus, several authors highlight the potential of a walking solution, *e.g.* [2,4,16]. Nevertheless, the most common vehicles are still wheeled or tracked, mostly because the development of a system with crawlers, legs and portable source of energy quickly becomes too complex, large, heavy and expensive [5].

Modular payload units for mine detection integrated in existing robots [15], blast resistant systems that deal with vegetation clearance [9], and tightly remote controlled systems [13] are the most common approaches to the mine clearance problem. Usually, robots move along the boundaries of the minefield while the sensors are placed above the terrain inside. Over

Table 1. Field Robots for Research in Humanitarian Demining.

	Type	Autonomy	Cost	Dimensions (L×W×H)	Speed (m/s)	Mine Handling	Additional Capabilities	Operation Time	Payload
 Gryphon-IV [14]	Four-wheeler all-terrain vehicle (Yamaha GRIZZLY 660)	Remotely Controlled or Manually driven	≥ 30,000€	2.08×1.15× 1.20 (m) without the long-reach 3 m manipulator	Typical: 1.5 Max: 5.0	Non-metallic pantograph arm with 3DOF with GPR and MD	Terrain modeling, Stereo vision, RTK GPS, Long Range WiFi	10 h Gasoline (25 L tank)	170 kg
 SILO-6 [16]	Six-legged walking robot (hexapod)	Semi-Autonomous	≥ 15,000€	1.38×0.95× 0.76 (m) without the ≈1 m manipulator, 71.34 kg	Typical: 0.1 Max: 0.5	5 DOF manipulator with IR range sensors placed around the MD	EKF fusing DGPS and odometry, Radio Ethernet, Electronic compass	1 h DC Batteries	5.7 kg
 RMA tEODor [17]	Heavy Tracked Outdoor Platform	Semi-Autonomous	≥ 50,000€	1.3×0.7× 1.24 (m) without the MD system, 350 kg	Max: 0.8	Multi-Channel system with 5 independent MDs	Adjustable soil compensation, Bumpers, 4 cameras, Traversability analysis, Long Range WiFi	2-3 h Lead-gel recharge-able battery; 4 x 12 V, 85 Ah	27 kg max: 200 kg
 ARES [18]	Four independ-ently steered wheels vehicle	Semi-Autonomous	≥ 7,500€	1.36×1.51× 0.66 (m), 80 kg	Typical: 0.5 Max: 1.0	TNT detection using odor sensor	Different locomotion modes, DGPS, magnetometer, Long Range WiFi, Sonars, Stereo Vision	4 h Lead-Acid Batteries	N/D
 FSR Husky [19]	Four-wheeler all-terrain vehicle (Clearpath Husky A200)	Semi-Autonomous	≈ 23,000€	0.99×0.67× 1.35 (m) without the mine-clearance arm, 70 kg	Max: 1.0	2 DOF mine-clearance arm with MD and artificial nose	2 stereo cameras, Pan/Tilt LRF, RTK GPS with IMU, Long Range WiFi	3 h Sealed lead acid 24V, 20Ah	20 kg max: 75 kg
 LOCOSTRA [20]	4 wheeled agricultural mini tractor with articulated skid steering	Remotely Controlled	≈ 50,000€	3.5×1.6× 2.15 (m) without the excavation system, 1850 kg	Typical: 3.0 Max: 8.3	Landmine removal by excavation	AP blast resistant wheels, Vegetation cutters, 2 IP cameras, Long Range WiFi	Diesel (50 L tank)	max: 1800 kg

the course of the mission, the robot slowly progresses inside according to the degree of belief on the absence of mines in the minefield [5].

Several field robots have been presented in the academic research context. These differ in their locomotion concept, autonomy, cost, size, weight, speed, operation time, mine detection system, capabilities and payload. A selection of wildly distinct platforms is presented in Table 1. Gryphon-IV [14] and LOCOSTRA [20] have given good indications in terms of mine detection in field trials. However, they are less suited to rough terrains when compared to robots with adaptable configurations like SILO-6 [16], tEODor [17] or ARES [18]. ISR-UC is currently working on the FSR Husky [19], which is a light-weight all-terrain vehicle being developed in the context of TIRAMISU FP7-EU project [13]. It should also be mentioned that other general use robots have already been applied in the military demining context, *e.g.* Minestalker, Talon or Packbot [6,15].

5. Research Trends

Despite recent advances, the development of a unique robot that can operate under all terrain and environmental conditions while meeting all demining requirements is not a simple task [2]. In their current status, robotized solutions are often expensive, unsafe, complex and inflexible [4,13], and are still best used as mobile platforms endowed with arrays of mine detection sensors with restricted decision-making capabilities. Nevertheless, a recognized effort has been made by several research groups to design autonomous robots in order to eliminate the permanent presence of an operator.

While heavy-duty mine clearance vehicles were popular as an alternative to manual demining, nowadays the focus has been put on developing small and cheaper mobile demining robots that can deal with confined spaces, and without having logistical problems associated with transportation to remote areas [6]. Similarly, the development of deformable machines that can get through narrow entrances has been discussed, *e.g.* [5], and the literature is consensual in pointing out that robots should follow modular mechanical structures, by separating mobility from manipulation and focusing on improving current robot platforms [2,4,7,13].

These machines can also be used in cooperation with dog teams and/or manual clearance teams, as well as unmanned aerial vehicles (UAVs), which may enhance localization, reconnaissance, trajectory planning and communications in rough environments, and also provide wide-area assessment [13]. Besides, swarm robotics is also attractive seeing as multiple, small and low-cost robots can coordinate their actions in the field, while speeding up the process and sharing experience on the identification of mines [6].

Concerning detection techniques, these are moving away from MDs due to the reduction of metallic content in modern mines, and the usage of diverse sensing modalities is increasing, taking advantage of classification algorithms, which have shown potential to reduce false alarms and provide more certainty in mine detection. Similarly, GPR based techniques are considered promising as they have obtained solid results in the field [8,12].

6. Conclusion

Research in robot technology for mine clearance is in the early stages and is slowly being transferred to the field. Despite its potential, there are many requirements to consider so as to reach production on a larger scale. Still, many lessons have been learned from several projects and experiences [13] and robots are already helping to accelerate search and mine detection, and increase safety in demining operations. Future research should focus on improved sensing devices, advanced mechatronics design, robot mobility, autonomous navigation in unstructured outdoor environments, energy efficiency, and robust manipulation in difficult field conditions.

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