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TriDem - A Wheeled Mobile Robot for Humanitarian Mine Clearance

***Abstract*—There are millions of lethal land-mines that have been left in many countries after a conflict. They represent a particularly acute problem in developing countries and nations already economically hard hit by war. The problem of unexploded mines has become a serious international issue, with many people striving to find a solution. This paper will discuss a wheeled mobile robot developed at the Royal Military Academy of Brussels in collaboration with Free University of Brussels, Belgium, in the framework of Humanitarian Demining Project (HUDEM).**

I. Introduction

MORE than 100 million of unrecovered anti-personnel and anti-tank mines can be found in more than 50 countries. It is estimated than mines hill or mutilate tens of people every day. In countries where the presence of landmines became a part of the everyday life, the consequences of landmines problem on humanitarian and environmental levels are very high (Colon *et al*., 1998; Habib, 2007; Habib, 2008).

There is an essential difference between military and humanitarian mine clearance operations in the Clearance Efficiency (CE). Military troops generally open a breach through a minefield while for humanitarian demining a high CE is required (99.6% according to UNO standards). This can only be achieved through a keen carding of the terrain and an accurate scanning of the infested areas, what implies the use of sensitive sensors and their slow systematic displacement, according to well-defined procedures on the minefields. This is where robots, carrying mine detectors, can play an important role (Colon *et al*., 2007).

It has been recognized that developing modular and cheap robotic systems that could offer reliable, cheap and fast solutions for the demining operations is an important challenge. The development and implementation of robotics in mine clearance is attractive and it is building up momentum to spare human lives and enhance safety by avoiding physical contact with the source of danger in mined area, improve accuracy, help in mined area reduction, increase productivity and enhance effectiveness of repetitive tasks, necessary in the demining process (Habib, 2008). Solving this problem presents challenges in robotic mechanics and mobility, sensors and sensor fusion, autonomous or semi autonomous navigation and machine intelligence.

Even if there are some reported researches into individual, mine-seeking robots is still at the early stages (Colon *et al*., 2002; Debenest *et. al*, 2003; Freese *et al*., 2006; Furihata and Hirose, 2005; Habumuremyi and Doroftei, 2001; Hirose and Kato, 1998; Hirose *et al*., 2005; Nonami et al., 2000; Tojo et al. 2004). In their current status, they lack flexibility and yet they represent a costly solution for mine clearance operation. But, if designed and applied at the right place for the right task, they can be effective solutions.

The automation of an application such as the detection and removal of antipersonnel mines implies the use of autonomous or teleoperated mobile robots. These robots follow a predefined path, send the recorded data to their expert-system (in charge of processing the collected data), mark the ground when a mine is detected with a probability of predefined level and possibly remove the detected mine.

The Belgian project HUDEM, which was focused on the detection, comprises three groups, each group dealing with one aspect of the problem. The first group was in charge of studying, evaluating and improving existing sensors, the second group developed algorithms to improve detection and the third one was responsible for robotics aspects. The Robotics Work Group was focused on: studying sustainable mechanical solutions for humanitarian mine clearance, developing of modular low-cost mobile platforms and developing of control algorithms using images of the environment and data coming from the mine sensors.

In this paper, the design of a simple, modular and cheap solution of wheeled mobile robot for humanitarian demining purposes will be described.

II. ROBOTIC SYSTEMS OVERVIEW AND REQUIREMENTS

Basically, the robotic systems for mine clearance are composed of the following elements: a vehicle, visual tracking and positioning systems, a control station with the Human Machine Interface.

The robotic systems for humanitarian demining can be divided into two categories: the ones having a scanning device that can be equipped with different sensors and the ones that can simply carry a single sensor. In this case, the scanning of an area can be obtained by moving the robot body itself. It is the case of our mobile robot described here.

Based on a state-of-the-art survey, we have defined some general requirements that a mechanical system for mines detection should meet and the possible solutions (see Table 1).

Reading the requirements, we will immediately find some contradictions: if we want to protect the vehicle and increase the autonomy, we also increase the weight; if we want to reduce the price, we have to use low cost, off-the-self components that do not resist very well to extreme conditions. We also have to limit electronic components, but these are essential to automate the mines detection and the motion control of the vehicle.

The best vehicle will result from a compromise between all these requirements. It is totally utopian to develop a vehicle that could be used in all circumstances: desert, wood,

TABLE I
REQUIREMENTS OF A ROBOTIC SYSTEM AND POSSIBLE SOLUTIONS

Requirements	**Possible solutions**
Low cost	Off-the-self technologies, large series
High mechanical reliability	Robust mechanics and electronics
Easy to service and repair	Modular design
Good resistance to explosions	Robust construction, a protection shield
Easy to deploy	Apparent limited command system
Easy to use	Simple Man Machine Interface
Easy transportable by a light vehicle	Light weight (Light materials)
Good autonomy	On board gas engine (stand alone or to produce electricity)
Water, sand, temperature and humidity resistant	Corrosion resistant material, high tech electronics

bush, hot or cold, wet or dry weather, etc. Furthermore, the characteristics of the vehicle will also depend on the way we will use it as explained in the next paragraph.

III. Mines Detection Strategy

Robotic systems could be used in different ways to help human deminers. Based on mine clearance teams' experience, the following scenario has been considered. Small autonomous vehicles equipped with different sensors run around to delimit the area of an assigned place that is really polluted with mines. This phase when done manually is one of the most dangerous one because deminers are working faster and are taking more risks than during a systematic detection. The mobile robot discussed here, named TriDem has been developed to study this first aspect.

Once the actual mined area is delimited, a systematic scanning process can begin. It has been proved that the use of different sensors could drastically improve the detection efficiency and reliability. However, the data fusion process requires the registration of the data acquired by the different sensors.

Our purpose is to develop systems to detect mines and not to destroy them. Based on this fact, we have also chosen to follow the existing demining procedures. When a mine has been discovered, its position is indicated with a beacon and the operation goes on in another corridor. Mines will be destroyed at the end of the day (or half of the day).

Different scenarios can be considered when replacing the man by machine. In the first scenario, we accept to sacrifice the robot; in this case we take the risk to roll over a mine and the vehicle must be disposable. In this case the sensors can be fixed everywhere on the robot.

The second scenario tries to preserve the robot. In this case, we cannot simply replace the man by a robot, because we will have to stop the robot each time when something has been detected and to go backwards and to maneuver to start in a new area. We also suppose that the mine zone is bordered by an area free of mines. The robot will follow the mine field while scan the ground laterally. Doing so, we do not have to stop the robot each time when a mine has been detected.

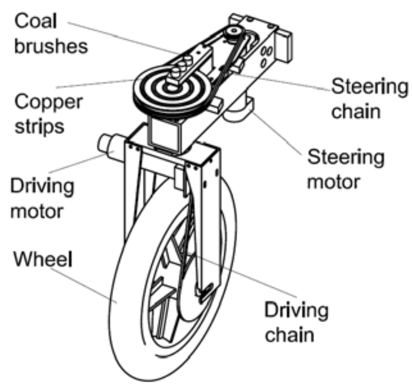
As everyone can imagine, the performance of a robotic system for humanitarian demining will rely principally on the quality of the detection system.

IV. TriDem Mobile Robot

Based on the requirements discussed in Table 1, we have designed a modular wheeled robot where each wheel module is equipped with a driving and a steering motor. Thanks to the three steered standard wheels, the robot has omni-directional capabilities.

A. Wheel architecture

The wheel module architecture is shown in Fig. 1. There are two motors connected to each wheel, one for steering and the other for driving. Therefore, each wheel has the capability of steering and driving independently. In order to prevent wires from becoming entangled, the power is transmitted to the driving motors using coal brushes and copper strips. This will give to the wheel a 360º rotation for steering motion.



(a)

(b)

Fig. 1. Wheel module: a) 3D design; b) Real picture.

The speed of each motor is reduced by using chain transmissions. To avoid cumulative mechanical errors of wheels in the mobile robot, the wheel alignment process is implemented. This process enables all three wheels to align, making it easier for the mobile robot to navigate. The wheel alignment process is made possible by a luminary point marked on the circular copper strips plate and a photo sensor.

B. Robot architecture

A construction using three wheels insures a permanent contact with the ground without adding any suspension. The repairing requirements lead us to a modular design of our robot: three similar units of driving and steering wheels are fixed on the main frame (see Figure 2). The fastening and the connections of the units to the frame should be as simple as possible to allow a quick removal. In case of breakdown or damage a module can be easily replaced by a new one. The defective unit will either be repaired locally or returned to the factory for more important repair, or thrown away if it is badly damaged.

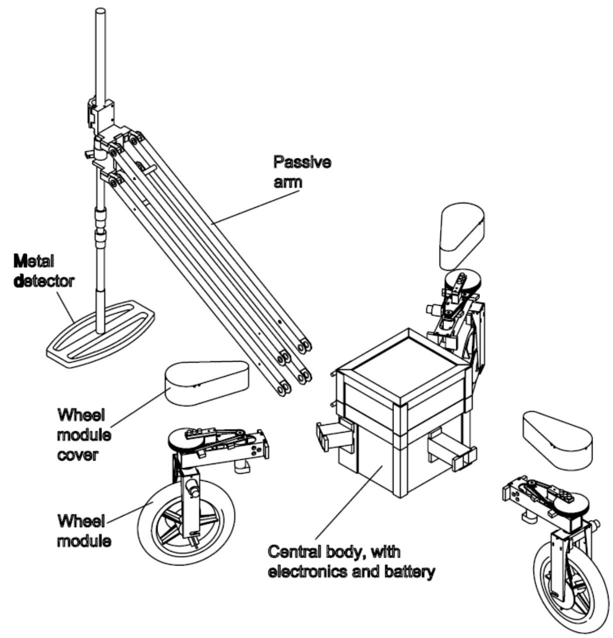


Fig. 2. Exploded view of the TriDem robot.

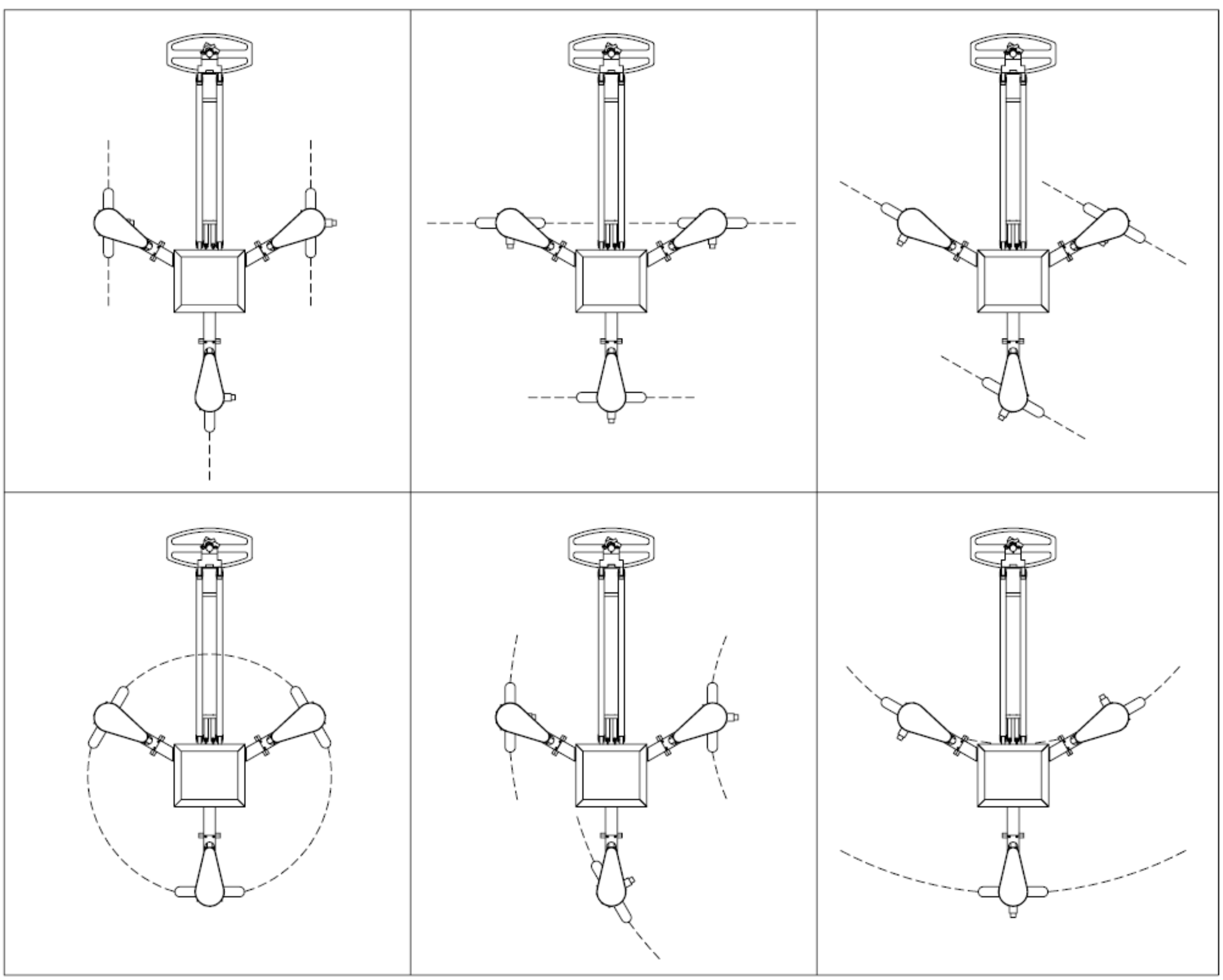


Fig. 3. Possible trajectories of the platform.

The wheels can be removed and replaced very easily because of the modular conception. All the wheel modules are identical and they are fastened to the robot frame with fast screw connections. The wires (signal and power transmission) of each wheel module are connected to the electronic board, placed in the central robot frame, via some standard connectors (DB15).

Thanks to the three steered standard wheels, we get an omni-directional mobile robot. It can perform a linear motion in any direction relative to its body; follow circular trajectories in different configuration or turn around its center (Figure 3). In contrast, a robot with synchronous drive can only perform linear motion. This means that a synchronous drive robot cannot follow smooth circular trajectories and cannot turn in place.

As drawbacks of this robot architecture, we can mention: the wheels should be very well aligned in order to avoid wheels slippage; when turning the wheels in place, on a surface with vegetation, it is happen with a high friction.

This platform can be used to locate minefields in areas that human deminers have difficulties to reach. For this reason, it has also been equipped with a spring articulated arm (with two parallelogram mechanisms) to carry light sensors. Springs are used to compensate the effect of gravity. This mechanism has one degree of freedom that allows the detector to move vertically in order to glide over obstacles. Thanks to this mechanism, the vertical axes of the robot and the one of the detector are permanently parallel.

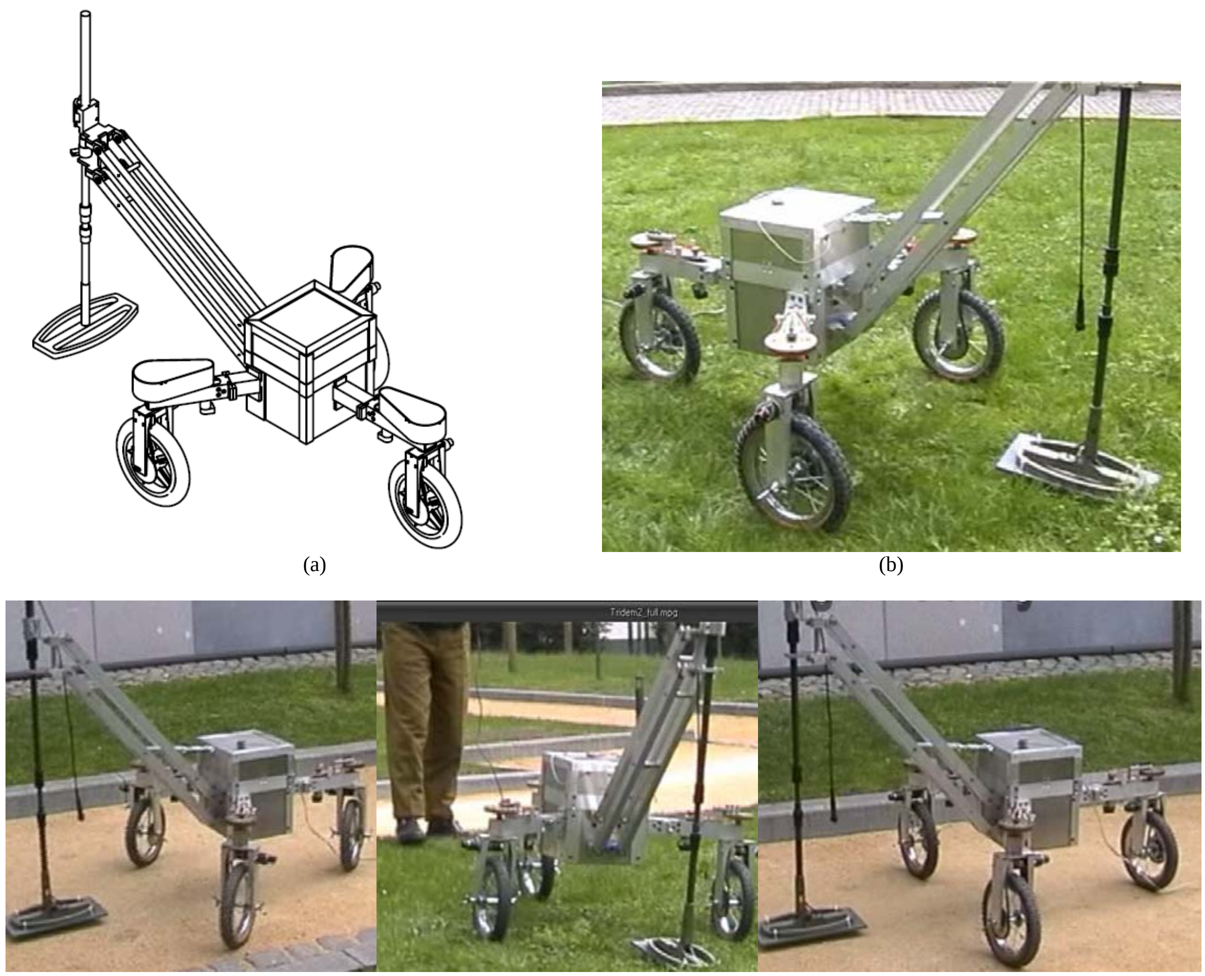
C. Robot control

TriDem mobile robot can be controlled by a wired joystick, a remote control or a computer via serial communication. Communication between the remote computer and the onboard microcontroller is assumed by a Radio link RS232.

The robot has been tested on dummy minefields and it performs well on gravels and grass but not on sand due to the limited size of the tires. As it was mentioned before, on the grass, the wheels turn in place with difficulties. It can clear small positive and negative obstacles (5 to 10 cm) with the detector still following the ground.

The robot frame supports holding the control electronics and the batteries. TriDem has been designed to have a 20-kg payload and a speed of 0.1 m/sec.

Figure 4 illustrates a 3D view of TriDem robot and different pictures during the real test on different surfaces.



(a) (b)

(c) (d) (e)

Fig. 4. TriDem wheeled robot: a) 3D design; b-e) real pictures during tests.

D. Robot kinematics

This section deals with the geometric kinematics modeling of TriDem omni-directional mobile robot. The kinematics modeling is divided into two parts, inverse kinematics and forward kinematics. Inverse kinematics is used to solve the angular velocities, ω_{w_i}, and steering angles, θ_{s_i}, of each wheel. Forward kinematics will estimate the position and heading angle of the mobile robot using the wheel measurement from the encoder.

It is assumed that there is no wheel slippage during the movement of the mobile robot.

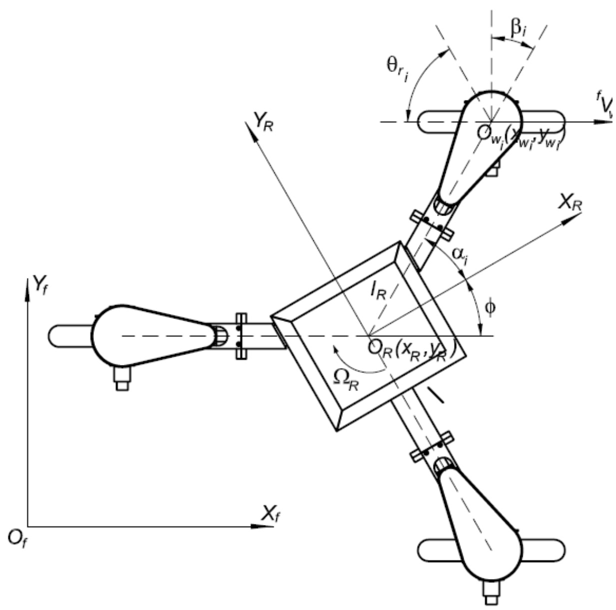


Fig. 5. Robot kinematics.

E. Inverse kinematics

We suppose to know: the linear velocities of the mobile robot in *X* and *Y* directions, ${}^{f}V_{l_x}$ and ${}^{f}V_{l_y}$, the angular velocity of the mobile robot, Ω_R, and the iteration number. Three coordinate systems are used in inverse kinematics: the floor coordinate system, $X_f Y_f$; the mobile robot coordinate system with its origin at the center of the platform, $X_R Y_R$; and, the wheel coordinate system with its origin at the center of each wheel, $X_w Y_w$. Each coordinate system consists solely of translation components, with no rotation components. A wheeled mobile robot's motion can be expressed in terms of translational and rotational motion. The translational component is the displacement of the mobile robot center, and the rotational component is the rotational movement of the axis of each wheel. Rotational components are expressed as follows:

$$\theta_{r_i} = \tan^{-1}\left(\frac{y_{w_i} - y_R}{x_{w_i} - x_R}\right) = \alpha_i + \beta_i\,, \qquad (1)$$

where θ_{r_i} is the angle between the direction of translational speed of the *i* wheel and the Y_R axis; x_R, y_R and x_{w_i}, y_{w_i} are the coordinates of the mobile robot's center and each wheel's center with respect to the origin of the floor coordinate system; $i = 1 \div 3$.

The rotational velocity of each wheel with respect to axes of the floor coordinate system, ${}^{f}(V_{rx})_i$ and ${}^{f}(V_{ry})_i$, can be calculated as follows:

$$\begin{cases} \left({}^{f}V_{rx}\right)_i = \Omega_R \cdot l_R \cdot \sin(\alpha_i + \beta_i) \\ \left({}^{f}V_{ry}\right)_i = \Omega_R \cdot l_R \cdot \cos(\alpha_i + \beta_i) \end{cases}, \qquad (2)$$

where l_R is the radial distance between the robot body center and the wheel center.

If we combine the known linear velocities of the robot with the rotational components (2), we get the linear velocity of each wheel:

$$\begin{cases} \left({}^{f}V_{wx}\right)_i = {}^{f}V_{lx} + \Omega_R \cdot l_R \cdot \sin(\alpha_i + \beta_i) \\ \left({}^{f}V_{wy}\right)_i = {}^{f}V_{ly} + \Omega_R \cdot l_R \cdot \cos(\alpha_i + \beta_i) \end{cases}. \qquad (3)$$

In these conditions, the steering angle of each wheel is

$$\theta_{s_i} = -\tan^{-1}\left(\frac{{}^{f}V_{lx} + \Omega_R \cdot l_R \cdot \sin(\alpha_i + \beta_i)}{{}^{f}V_{ly} + \Omega_R \cdot l_R \cdot \cos(\alpha_i + \beta_i)}\right) + \Omega_R \cdot t_s\,, \qquad (4)$$

where t_s is the steering time, and the total linear velocity of each wheel will be as follows:

$${}^{f}V_{w_i} = \sqrt{\begin{aligned}&\left[{}^{f}V_{lx} + \Omega_R \cdot l_R \cdot \sin(\alpha_i + \beta_i)\right]^2 + \\ &+ \left[{}^{f}V_{ly} + \Omega_R \cdot l_R \cdot \cos(\alpha_i + \beta_i)\right]^2\end{aligned}}\,. \qquad (5)$$

Once the velocity of the wheels is calculated, angular velocities of the each wheel can be found,

$$\omega_{w_i} = \frac{{}^{f}V_{w_i}}{r_w}\,, \qquad (6)$$

where r_w is the wheel radius.

F. Forward kinematics

Forward kinematics is used to estimate the position and heading angle of the mobile robot using the angular increments of each wheel, measured with encoders. Firstly, the rotational and steering values of the wheels are measured and obtained from translational and rotational components at the mobile robot center. Velocity components of each wheel, measured with respect to the robot coordinate system are given as

$$\begin{cases} \left({}^{f}V_{wx}\right)_i^m = -\left({}^{f}V_w\right)_i^m \cdot \sin\left[\left({}^{f}\theta_{s_i}\right)^m + {}^{R}\Omega_R^m(k-1)\cdot t_s\right] \\ \left({}^{f}V_{wy}\right)_i^m = -\left({}^{f}V_w\right)_i^m \cdot \cos\left[\left({}^{f}\theta_{s_i}\right)^m + \Omega_R^m(k-1)\cdot t_s\right] \end{cases}. \quad (7)$$

Using the property that the rotational components are canceled if the velocities of the three wheels are added together, the translational components of the robot velocity are obtained as:

$$\begin{cases} \left({}^{f}V_{lx}\right)^m = \sum_{i=1}^{3} \frac{\left({}^{f}V_{wx}\right)_i^m}{3} \\ \left({}^{f}V_{ly}\right)^m = \sum_{i=1}^{3} \frac{\left({}^{f}V_{wy}\right)_i^m}{3} \end{cases}. \quad (8)$$

Using eq. (6)-(8), the coordinates of the mobile robot's center and each wheel's center are obtained as follows, with respect to the origin of the floor coordinate system:

$$\begin{cases} x_R(k) = \left({}^{f}V_{lx}\right)^m \cdot t_s + x_R(k-1) \\ y_R(k) = \left({}^{f}V_{ly}\right)^m \cdot t_s + y_R(k-1) \end{cases}, \quad (9)$$

$$\begin{bmatrix} x_{w_i}(k) \\ y_{w_i}(k) \end{bmatrix} = \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \cdot \begin{bmatrix} x_{w_i}(k-1) - x_R(k-1) \\ y_{w_i}(k-1) - y_R(k-1) \end{bmatrix} + \begin{bmatrix} x_R \\ y_R \end{bmatrix}. \quad (10)$$

The angular velocity of the mobile robot is obtained from the amplitude and its directions as follows:

$$\Omega_R^m = \frac{\sqrt{\left[\left({}^{f}V_{rx}\right)_i^m\right]^2 + \left[\left({}^{f}V_{ry}\right)_i^m\right]^2}}{r_w}, \quad (11)$$

where

$$\begin{cases} \left({}^{f}V_{rx}\right)_i^m = \left({}^{f}V_{wx}\right)_i^m - \left({}^{f}V_{lx}\right)^m \\ \left({}^{f}V_{ry}\right)_i^m = \left({}^{f}V_{wy}\right)_i^m - \left({}^{f}V_{ly}\right)^m \end{cases}. \quad (12)$$

In this case, the direction of the angular velocity should be determined considering positions of each wheel by the mobile robot's coordinate system.

V. CONCLUSION

The robot we are developing demonstrates a great potential for humanitarian demining application. Its simplicity, modular architecture and low cost make the robot a real candidate for such applications. It is sure that we did not solve the anti-personnel mines problem with this preliminary project, and perhaps our efforts are like a drop in the ocean, but we know that many people all over the world are working in the same direction. So, we are sure that, together, we may give some positive results in a near future.

ACKNOWLEDGMENT

The results will be further implemented thanks to the EC FP7 GA 284747 TIRAMISU Project.

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