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Demining Robots – Requirements and Constraints

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Review

One of the most urgently needed applications for mobile robots is demining. Using robots in a minefield is accomplished with severe demands for mobility in an environment covered with dense vegetation and containing various obstacles. Furthermore, it is required that robot should cover the whole area with the detector, avoiding previously detected mines. Different configurations of demining robots are analyzed regarding control and navigation, size and locomotion.

Key words: demining, mobile robot

1 INTRODUCTION

Landmines present a threat to population in many countries. Demining campaign is characterized with high cost, low efficiency and high risk for deminers. Although humanitarian demining procedures are improved and standardized recently, technology has not changed much since the World War II.

Demining is still based on combination of four basic methods and corresponding equipment: prodder, metal detector, machine, and a dog. *Prodder* consists of 30 cm long prod that deminer inserts into the soil at a shallow angle (approximately 30 degrees). When the prod touches something hard the operative will begin »feeling« the contour to find out whether it is a rock, debris or a mine. The manual probing is slow, hazardous and stressful process. *Metal detectors* expose a conductive object to a time-varying magnetic field. The secondary magnetic field resulting from eddy currents induced in metal parts of an object is detected. Mines with low metal content (few grams) pushes metal detectors to their limits. High sensitivity necessary to detect such mines implies high false alarm rate that often turns metal detector useless. *Machines* destroy or activate mines mechanically, by hitting or milling the ground. Under certain conditions (flat land, medium sized vegetation) they can be very efficient. *Dogs* are the best known explosive detectors. However, they need excessive training, and are inherently unreliable. From this short overview it is clear that no single method can be used under all circumstances. Therefore a combination of at least two different methods is used, e.g. machine followed by a dog, or metal detector and prodder.

Humanitarian demining procedures differ significantly from military procedures. Military needs to breach narrow path through the minefield as fast as possible and with acceptable loses due to missed mines. On the opposite side, humanitarian demining requires 100 % detection and removal of all mines on large area. Furthermore, coverage of the whole area is required. Time is not important, although it may significantly influence the cost of operation.

Demining process consists of three stages: suspected area reduction, actual demining, and quality control. Although similar equipment and methods are used, goals are different. Area reduction is performed to distinguish mined area from the area that is not mined. In actual demining it is necessary to detect, localize, and remove each individual mine. Quality control is performed prior to issuing a certificate that the area is safe [2].

One of the reasons that new methods and technologies are slowly entering into the minefields is a gap between scientists and deminers, were deminers are often unable to articulate their requirements, and scientists do not understand the problem: what they are looking for (what is mine), in which conditions (what is the minefield and how it looks like), and what are the demining procedures and standards that the new equipment should meet. Most of the scientific effort is directed toward development of a successful detection technology. All detection methods have in common that they are looking for some distinctive feature of the mine against the background. Varying background conditions (soil type, humidity, vegetation, etc.) makes sensor development and signal analysis difficult. Features include explosive content (various nuclear and chemical methods), metal content (metal detectors), dielectric properties (ground penetrating radar (GPR), conductivity measurements), acoustic properties (ultrasound), thermal conductivity (IR detectors), etc. An overview of various detection technologies can be find in [12].

The task for a mobile robot is to detect mines, mark them and eventually destroy them. Generally robots should improve quality of tasks performed by humans, and release human beings from working in hazardous environment. That already happened in 70's and 80's with industrial robots.

Working in a minefield is not an easy task for a robot. Hostile environmental conditions and strict requirements dictated by demining procedures make development of demining robot a challenge. But is it easier to build a robot for exploration of Mars then for demining?

Different approaches to using robots for demining exist, including adaptations of current detection methods, proposals of various robot designs, and utilizing groups of robots. Automation of prodding is proposed in [1] and [8]. In [15] Pemex, the medium size wheeled robot is described. Large teleoperated platform equipped with various sensors is described in [7]. Possibilities for using walking robots for demining are analyzed in [17] and [22]. In [9] and [14] authors analyzed desired behaviors of group of small robots. Some prototypes left laboratory entering the test field, but none of them yet enters the minefield.

2 REQUIREMENTS

Humanitarian demining standards and requirements define desirable features of a demining robot. Although demining procedures may and should be modified to utilize full potential of new equipment, they should still guarantee:

- detection of mines in all conditions with near 100 % probability,
- complete coverage of defined area.

Detection capabilities are dictated by sensor(s) used and will not be a subject of further analysis. Area coverage is the responsibility of the robot. To accomplish that goal, robot should be able to:

1. *Follow the defined search pattern*. During the preparation of certain demining task off-line planning should be performed, preferably using high precision digital maps and aerial photographs [2]. Search pattern may be defined in advance, already taking into consideration some environmental constraints.
2. *Negotiate difficult terrain* (see Figures 1–6). Although most of the path planning might be performed in advance, working in natural environment should impose a level of reactive control, to be able to avoid obstacles and impassable regions.
3. *Record and report position during the whole mission*. Due to environmental constraints robot will not always be able to follow planned search pattern. After the robot performs its mission it is important to know if some parts of the area were skipped. Such parts should be checked manually.
4. *Work fast enough to be cost-effective*. Deminer with a prodder and a metal detector may check average 2–20 m^2 per hour. Machine may pass 1.000–10.000 m^2 per hour, but with lower probability of discovering (destroying) mines. Robots should be faster than a human and will probably be slower than machine, but retaining high probability of detection.

3. ENVIRONMENT

Common mistake is to conceive a minefield as a mowed lawn, or even construct a »block world« representing the minefield. Although such simplifications and abstractions are sometimes useful to study

Fig. 1 Agricultural land without vegetation is easy passable

Fig. 2 In few years vegetation cover could make it impassable

Fig. 3 Rock-bound coast covered with macchia

Fig. 4 Macchia

Fig. 5 Mined area covered by macchia, divided by stone walls

Fig. 6 Mined house vicinity

and develop navigation algorithms and robot behaviors, they also implicit undesirable level of abstraction. It is best to use world as its own model [6].

Main characteristic of minefields is diversity of vegetation, soil, humidity, slope, and other environmental conditions. Agricultural land shown in Figure 1 is easy passable, but after few years it may turn into something like in Figure 2.

Rock-bound coast (Figure 3), fields covered by rocks and macchia (Figures 4, 5) and house vicinity (Figure 6) are examples of different mined areas. Photos present some mined areas in different parts of Croatia.

4 CONTROLAND NAVIGATION

Control system of the robot should be able to negotiate harsh environment of the minefield, and at the same time navigate through the area with surgical precision. Requirements to the task that robot should perform are normal for ordered industrial environment, but it should be performed in unknown and unordered world.

Behavior based approach for controlling mobile robots was introduced in 1987 by Brooks [5] and since then attain lot of attention. That concept has proven on some important mobile robot projects. Mars Pathfinder microrover successfully performed first space mission involving autonomous robot [21], and six-legged robot Dante explored a remote Alaskan volcano [3]. In behavior based approach the problem is decomposed in task achieving behaviors, rather than in series of functional units connecting sensors to actuators. Behavior based architecture is based on layers with different levels of competence. Lowest layer is usually responsible for obstacle avoidance and higher layers are containing various tasks oriented behaviors. Lower level behaviors normally have higher priority (to avoid obstacle is more important for the survival of the robot than to follow the defined path). There are approaches to include reinforcement learning that alters the behavior triggering scheme. For the demining robot, simple fixed priority layer organization will be adequate. Although robot should move in difficult environment, task it should perform is well defined, simple and straightforward.

For a demining robot, the highest layer should be responsible for navigation. Navigation layer gui-des robot through the predefined path that guaran-tees coverage of target area. Environmental con-straints should, through appropriate sensors, trigger lower level behaviors responsible for obstacle avoid-ance and stability maintenance. Deviations from predefined search path caused by environmental in-fluences should be recorded. At the end of the mission, checked and skipped area should be clearly marked at the digital map of the terrain, together with mine targets found.

Search pattern may and should be defined off--line, using digital model of a terrain. Example of the search pattern is shown in Figure 7.

Fig. 7 Search pattern

To be able to perform desired task, robot should be equipped with appropriate sensors. Sensors can be divided into following groups: internal, environmental, navigational, and task related.

Internal sensors are responsible for monitoring internal state of the robot, like temperature and available power.

Environmental sensors give robot information about the surroundings necessary to avoid obstacles and negotiate the environment. Ultrasonic and IR sensors extensively used indoors are not so reliable in natural environment. Wider variety of obstacles can affect reliability of those sensors. Tactile sensor is less dependent on obstacle surface and other properties, but to detect the obstacle, robot should obtain physical contact. Vision, extensively used in industrial environment, is at the current level of development useless outdoors, because the scene is to complicated for real time analysis with reasonable computer power. Analysis could be simplified using camera together with the laser stripe projector. Appropriate sensor should also be able to detect whether obstacle is passable (e.g. to distinguish grass from bushes).

Navigational sensors [4] are giving the information about global orientation and position. Sensors attached to the actuators (e.g. optical encoders on wheels) can be used for dead reckoning (calculation of global position by accounting incremental changes in position and orientation). Serious drawback of dead reckoning is accumulation of error. Accumulated error could be reduced using heading sensor: gyroscope or compass. For global positioning, ground--based RF-beacons and global positioning system (GPS) can be used. GPS is not accurate enough to be used as navigational sensor, but with recent advances in differential GPS (DGPS) devices it is possible to keep positional error below 10 cm. Much simpler approach is feasible. Robot could leave appropriate marks behind, thus knowing the boundaries of previously searched area. Similarly, deminers mark already checked area by leaving lines behind.

Task related sensors for demining robot are mine detectors. It is interesting how properties of mine feature, detector is looking for, influences required accuracy of navigational sensor. If the mine detector is looking for a mine as an object buried in the soil, global positioning accuracy should be high because detector should pass directly over the mine to detect it. If the detector is looking e.g. for an explosive odor evaporating from the mine, lower global positioning accuracy is allowed because mine signature occupies larger area. In that case gaps in searched area are allowed, even desirable, because it can increase the search speed. That is exactly the way that area reduction using dogs is performed.

5 SIZE

Size of a robotic platform is an important issue, dictated by the size of available mine detector, environmental constraints, power supply, capacity (area/time), price, etc. As human beings, we are used to look terrain from the point dictated by our own size. It is not easy to imagine how the same terrain will look from the standpoint of an elephant, or an ant. Is it more effective to build one huge robot that will be powerful enough to destroy or go across the obstacles, or bunch of small ant--sized robots?

Realistic environment is covered with vegetation of various sizes, containing rocks, holes, roots and other different sized obstacles, steep slopes and trenches. All those obstacles will have different properties and negotiability according to the size of the robot. Vegetation covers the height range roughly from 10^{-1} m to 10^{1} m. Building robot 10 m large (or long) will be very expensive. Also, using brute force to pass through the vegetation is not always desirable. If vegetation is the main value of certain area, it should be preserved. Large robot will also have the problem with detected mines. It is not cost effective to remove or destroy each mine im-mediately after detection. That will impose additional constraints to the robot motion, because robot will have to avoid detected mines. Tripwires present additional problem. They are hard to detect, and even harder to avoid.

When the size is reduced bellow the centimeter range, natural paths are starting to open through the vegetation. We can learn the lesson from the nature: *Ant is more mobile than an elephant*. For a robot weighting couple hundreds of grams, detected mines and tripwires are not a problem anymore. Even the most sensitive mines have the actuation force greater than 10 N, which means that the small robot can move freely over the minefield.

6 LOCOMOTION

Mobility of a robot is highly dependent on the type of locomotion. Unfortunately, constructions with better mobility are usually slower, harder to build and control, and more expensive.

Wheels and tracks are most widely used, and are well known from various types of vehicles. Tracks allow better mobility then wheels, but they are less energy efficient and due to the extensive slippage, especially during changing direction, makes odometry and dead reckoning virtually impossible. Careful design of wheels kinematic structure can also result in high mobility [21].

Legged robots usually mimic insects, i.e. they have more than four legs for better stability. They are much slower than wheeled robots, but they have higher mobility [3].

Worm like structures may offer even higher mobility [16]. Movement is achieved by transposition of supporting links by longitudinal traction waves. Fact that all but one links may be supporting at particular moment, makes possible climbing steep slopes. Such a structure usually has small cross section that makes possible moving through narrow paths.

Unmanned aerial vehicle (UAV) will be the best solution. Helicopter or zeppelin structure should be appropriate for mine detection. The main problem with aerial platforms is that they move the mine detector away from the mine, making it much harder to be detected. Vegetation cover can also signi-ficantly reduce ability for airborne detection.

7 USING MULTIPLE ROBOTS

Alternative approach of using one big robot will be to use large number of small, inexpensive robots [10, 11, 13, 18]. That approach is in accordance with above conclusion that smaller robot has better mobility.

Small robot will unavoidably be slower. Idea is to compensate for the lower speed with larger number of individual units. Smaller size also means reduced capabilities. On a centimeter-sized robot it is not feasible, nor cost effective to put e.g. DGPS. Therefore it is necessary to develop appropriate group behaviors to compensate for reduced capability of individual units.

Possible scenario might be to use large number of individual units working side-by-side, together searching wider area. Figure 8 presents search patten for the group of robots working in parallel.

Fig. 8 Search pattern for the group of robots working in parallel

Minimal set of behaviors to maintain the search pattern will be »keep direction«, and »keep longitudinal and lateral distance to the neighbors«. For maintaining required direction compass or piezoelectric gyroscope is sufficient. For determining longitudinal and lateral distance to neighboring robots, each robot needs to have some kind of an easily detectable beacon and detector capable of measuring distance and direction of a neighboring beacons. Distance may be measured through intensity of a signal from the beacon. Besides keeping direction, all that robots need to do is to stay within predefined minimum and maximum distance form their neighbors. Closer look of robot interrelations is presented in Figure 9.

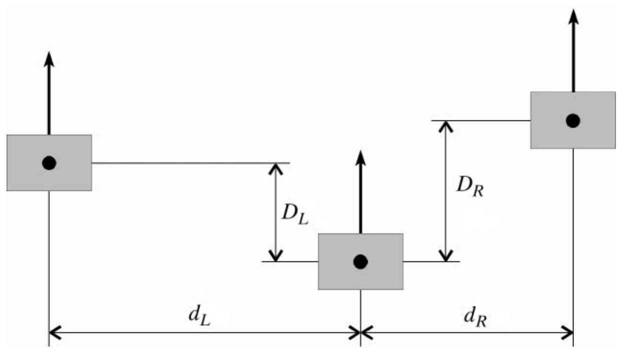

Fig. 9 Interrelations of neighboring robots

From the distance and the angle of the neighboring robot beacon, middle robot will calculate distances to the left and right neighbors. Appropriate behavior for longitudinal distance correction will be to increase or decrease speed to reduce distance D_L to the left neighbour. To avoid grouping together or diluting, lateral distance correction behavior should take into consideration minimal and maximal allowed distance. The robot should adjust its lateral position according to the one of the neighboring robots, e.g. the left one. Thus behavior of keeping appropriate lateral distance will propagate through the group from the left edge. To keep robots within desired area, the leftmost robot has to follow appropriately marked left boundary. In addition, both leftmost and rightmost robots should leave appropriate marks behind for later reconstruction of boundaries of examined area.

Proposed control of the particular robot for the desired group behaviour can be tested by the simulation. For this purposes, it is necessary to determine the simplest possible model of the particular mobile robot. The position and the velocity vector of the i^{th} robot, according to the Figure 10, can be described by its speed and orientation.

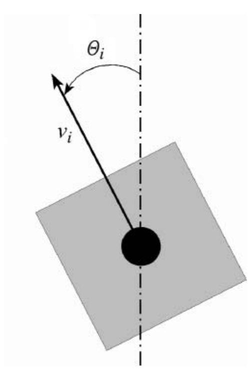

Fig. 10 Orientation and speed of the ith robot

The model of the particular position-controlled robot can be described by the following velocity and orientation transfer functions:

$$G_{vi}(s) = \frac{v_i(s)}{v_{ir}(s)} = \frac{1}{T_{v1}T_{v2}s^2 + T_{v2}s + 1},$$
$$G_{\Theta i}(s) = \frac{\Theta_i(s)}{\Theta_{ir}(s)} = \frac{1}{T_{\Theta 1}T_{\Theta 2}s^2 + T_{\Theta 2}s + 1}, \qquad (1)$$

where:

$G_{vi}(s)$ – velocity transfer function of the i^{th} robot,
$G_{\Theta i}(s)$ – orientation transfer function of the i^{th} robot,
T_{v1}, T_{v2} – time constants of the velocity transfer function,
$T_{\Theta 1}, T_{\Theta 2}$ – time constants of the orientation transfer function,
v_i – velocity of the i^{th} robot,
v_{ir} – referent velocity of the i^{th} robot,
Θ_i – orientation of the i^{th} robot,
Θ_{ir} – referent orientation of the i^{th} robot
s – Laplace operator.

The position of the i^{th} robot is determined by its velocity, orientation and position initial condition. Therefore, the position equation of the i^{th} robot has a form:

$$x_i(t) = x_{0i} + \int_0^t v_{xi}(\tau)\mathrm{d}\tau = x_{0i} + \int_0^t v_i(\tau)\sin[\Theta_i(\tau)]\mathrm{d}\tau,$$
$$y_i(t) = y_{0i} + \int_0^t v_{yi}(\tau)\mathrm{d}\tau = y_{0i} + \int_0^t v_i(\tau)\cos[\Theta_i(\tau)]\mathrm{d}\tau, \qquad (2)$$

where:

$x_i(t)$, $y_i(t)$ – absolute coordinates of the i^{th} robot,
x_{0i}, y_{01} – position initial conditions of the i^{th} robot,
v_{xi}, v_{yi} – velocity components in x and y direction,
t – time.

Velocity reference v_{ir} can be computed according the criterion of keeping longitudinal distance D_L (Figure 9) to the left robot. For this reason, the simple proportional type referent velocity generating algorithm could be developed. The algorithm has a form:

$$v_{ri} = K_{vi} \cdot D_{Li} = K_{vi}(y_{i-1} - y_i), \qquad (3)$$

where:

K_{vi} – proportional gain of the velocity regulator of the i^{th} robot,
D_{Li} – desired longitudinal distance,
y_{i-1} – longitudinal position of the left robot.

If the position of the right robot should be taken into consideration in case of a possible malfunction of the right robot, the referent velocity algorithm should be revised. In case of increase of the longitudinal distance between i^{th} and i+1st robot over permitted value, the i^{th} robot should be stopped. Therefore, the velocity algorithm has a form:

$$v_{ri} = \begin{cases} K_{vi}(y_{i-1} - y_i), & \forall |y_i - y_{i+1}| < D_{R\max}, \\ 0, & \forall |y_i - y_{i+1}| \geq D_{R\max}. \end{cases} \quad (4)$$

Possible oscillations caused by v_{ri} according to equation (4) could be avoided by applying the hysteresis block to the v_{ri} signal. The proposed velocity reference algorithm could be valid for all robots except the first left one. The same algorithm could be applied to the first robot if the velocity reference is limited and the final y position of the search area is used as a y_{i-1} value.

The referent orientation signal is determined by similar proportional algorithm dependent on the lateral distance to the i–1st robot. The algorithm could be described by the following equation:

$$_{ir} = K_{\Theta i}(x_i - x_{i-1} - d_{Lir}) \quad (5)$$

where:

- $K_{\Theta i}$ – proportional gain of the i^{th} robot orientation reg.,
- x_i, x_{i-1} – lateral position of the i^{th} and i–1st robot,
- d_{Lir} – desired lateral distance.

The reference orientation Θ_{ir} should be limited to the interval [–π/2, π/2] to avoid change of direction. The algorithm described by the equation (5) is applicable to all robots except to the first one. The referent orientation of the first robot should be constant and equal to the desired angle of moving. The obstacle detectors should have higher priority than the proposed orientation algorithm, so the orientation could be changed due to detected obstacles in robot paths. The influence of the obstacles detector to the robot path could be simulated by adding orientation disturbance signal in equation (5).

Described behavior for group of five robots is simulated. Simulation results are shown in figures 11 to 13: Figure 11 presents resulting trajectories in the x-y plane, Figure 12 velocities and Figure 13 positions.

Appropriate mine detector for described configuration may be an odor sensor, consisting of a quartz crystal coated with layer that attracts molecules of explosive. That results in slight, but detectable change of resonant frequency. Such detectors exist, but their sensitivity is still to low. When the mine is found it should be appropriately marked. Size of the robot limits possible marking methods. The mark should be detectable from the outside or from the above of the checked area. The possibility is to mark mines with fluorescent painting.

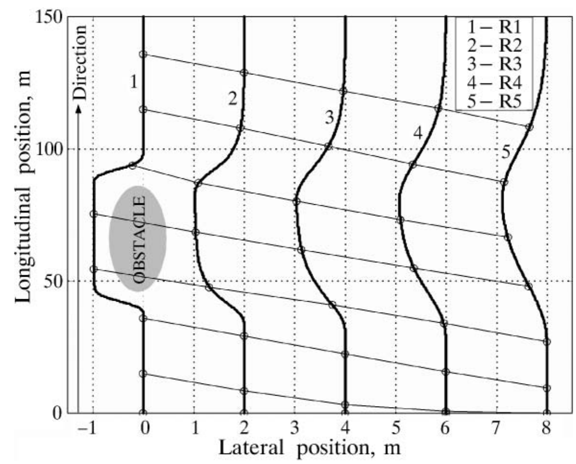

Fig. 11 Robots trajectories in x-y plane

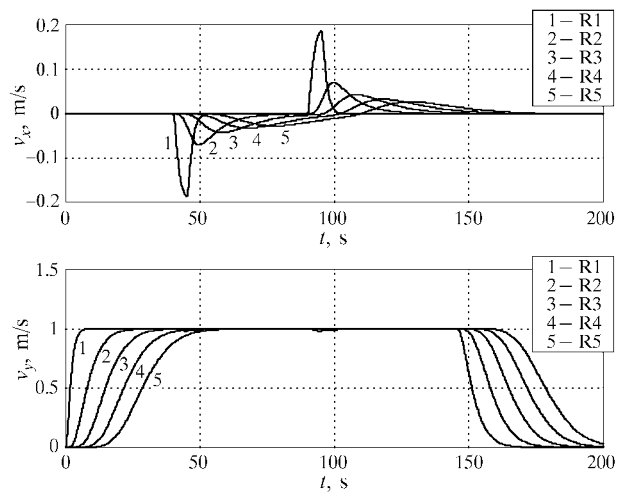

Fig. 12 Robots velocities in x and y direction

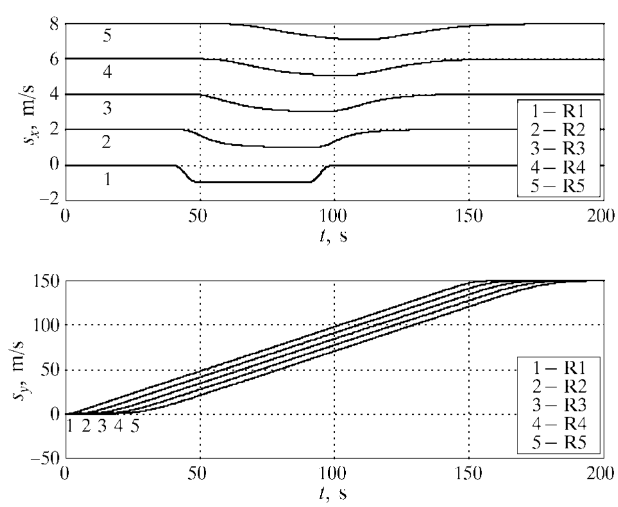

Fig. 13 Robots positions in x and y direction

8 POSITION TRACKING

Tracking of detector or tool position is the first step toward automation of the terrain search procedure. Although far from complete autonomy and automation of the demining process, such a system is directly applicable to existing remote controlled demining machines. For position and orientation measurements a differential GPS receiver (DGPS) attached to the appropriate place at the platform could be used. It is possible to determine position of the detector from the position and orientation of the platform reference vector. Origin of the reference vector is defined by position of the DGPS receiver and its orientation with direction of movement.

Figure 14 shows mobile platform with DGPS receiver mounted at the point T_0. All measures and angles required for calculating position of the detector are marked.

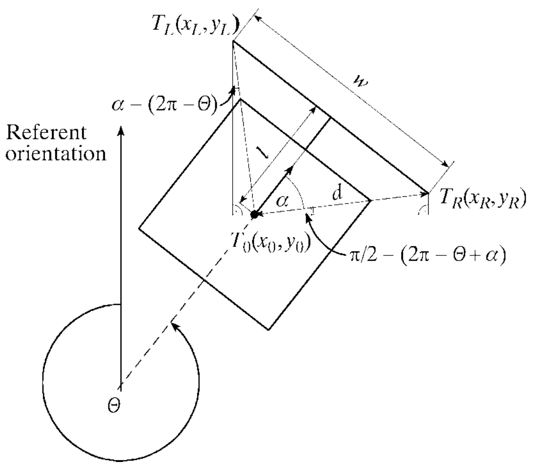

Fig. 14 Calculating the detector position

Coordinates of the left and right edge of the detector are determined by following equations:

$$x_R = x_0 + d\cos\left(\frac{\pi}{2} - 2\pi + \Theta - \alpha\right) = x_0 - d\sin(\Theta - \alpha)$$

$$y_R = y_0 + d\sin\left(\frac{\pi}{2} - 2\pi + \Theta - \alpha\right) = y_0 - d\cos(\Theta - \alpha)$$

$$x_L = x_0 - d\sin(\alpha - 2\pi + \Theta) = x_0 - d\sin(\Theta + \alpha) \tag{6}$$

$$y_L = y_0 + d\cos(\alpha - 2\pi + \Theta) = y_0 + d\cos(\Theta + \alpha)$$

$$d = \sqrt{\frac{w^2}{4} + l^2}\,,\ \alpha = \arctan\left(\frac{w}{2l}\right),$$

where:

- x_R, y_R – coordinates of the detector right edge,
- x_L, y_L – coordinates of the detector left edge,
- x_0, y_0 – reference point coordinates where the DGPS receiver is attached,
- w – detector width,
- l – distance of detector axis from the reference point,
- Θ – platform angle from the reference orientation,
- d – distance of detector edges from the reference point,
- α – angle between platform longitudinal axis and line connecting reference point and the detector edge.

In the case that the detector is positioned asymmetrically to the platform longitudinal axis, the detector width should be defined using w_L and w_R, and associated d_L, d_R, α_L and α_R should be calculated accordingly.

Figure 15 presents simulation results for a group of five robots working in parallel. The left side of the figure presents recorded trajectories and the right one calculated detector positions. Area covered by the detector and skip zones caused by environmental constraints could be easily observed. Important information could be extracted from the collected data. Reported skip zones could be easily recognized to be checked later manually. Total examined area could be reported and documented. Quality control could be documented as well, giving higher confidence level in safety of the cleared area.

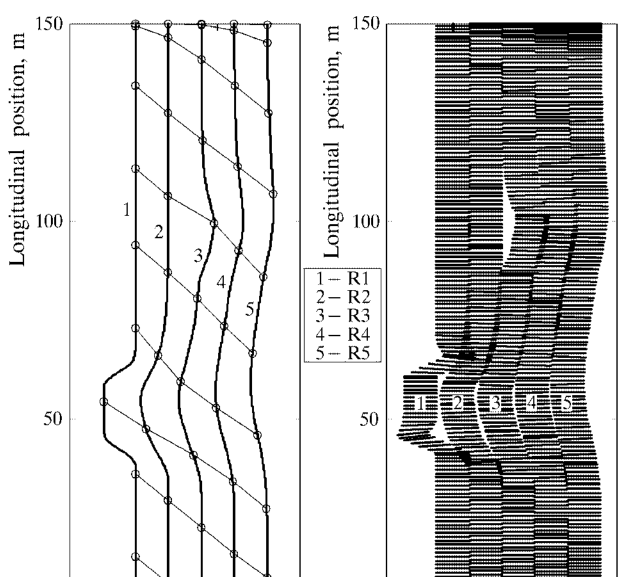

Fig. 15 Robot trajectories and the area covered by the detector

9 CONCLUSION

Demining is an area where mobile robot could mean the difference between the life and the death. Designing mobile robot to work in a minefield is accomplished with a lot of difficulties. To be able to design and build successful robot it is necessary to carefully study conditions and constraints of the demining operation. Design of the robot should reflect demining requirements and constraints. To test the design it is necessary to build the robot and develop its behavior in natural environment. Suggested direction for further research is grouping of the large number of small, simple robots working together.

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Roboti za razminiranje – zahtjevi i ograničenja. Razminiranje je jedno od najvažnijih potencijalnih područja primjene mobilnih robota. Korištenje robota u minskom polju povezano je sa strogim zahtjevima na pokretljivost u okolišu prekrivenom gustom vegetacijom koji sadrži različite prepreke. Povrh toga, robot mora omogućiti pregled cijelog područja detektorom, izbjegavajući prethodno otkrivene mine. U radu su analizirane različite strukture robota za razminiranje s obzirom na upravljanje, navigaciju, veličinu i način kretanja.

Ključne riječi: mobilni robot, razminiranje

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