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A Navigation and Control System for a Mobile Robot for Patrolling Buildings

Robert GŁĘBOCKI, Paweł KICMAN, Antoni KOPYT*

Warsaw University of Technology, Faculty of Power and Aeronautical Engineering,
24 Nowowiejska Street, 00-665 Warsaw, Poland
**Corresponding author's e-mail address: akopyt@meil.pw.edu.pl*

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Abstract. This paper presents the work completed under a research project titled „Design of a mobile platform for the support of forensic testing of scenes with potential CBRN hazards". The study focuses on operation of the mobile platform control algorithm, determination of the mobile platform position and preparation of the mobile platform system for integration with a video navigation system. The sensors installed on the mobile platform are intended as emergency backup systems in the event of loss of communication between the platform and its operator. The results of the test drive sessions completed to verify the control algorithm performance are also given.

Keywords: robotics, mobile robot, control, data fusion

1. OPERATION OF A MOBILE ROBOT IN INDOOR SPACES

The mobile platform contemplated herein is intended for forensic work in ambient conditions with potential CBRN hazards. During their operations, police teams of forensic technicians may encounter CBRN hazards.

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They often prevent forensic work and collection of evidence, which highly inhibits criminal investigation, apprehension and evidence presentation in a court of law. To counter this, a police robot has been developed. It is capable of replacing police forensic technicians on scenes with health or life hazards from CBRN contamination.

The mobile platform which constitutes the police robot is controlled remotely via RF communication by an operator who interacts according to the visual feed from the mobile platform video cameras. However, as the mobile platform is generally operated in indoor spaces, there is a risk of interruption of the RF communication. During its operations, the mobile platform often manoeuvres in basements and other rooms cut off from the operator by thick walls. This operating environment often results in the loss of the RF communication, making the mobile platform control inoperable. If a CBRN contamination hazard is present, it is not possible to send personnel to the scene and re-establish the RF communication with the mobile platform. It is then necessary for the mobile platform to automatically backtrack along its memorized route of entry to a position where it is possible to re-establish the RF communication and control by the operator.

Another issue related to the mobile platform is the restricted vision of the operator who monitors the visual feed from the mobile platform cameras, especially if there is trace evidence on the floor at the forensic scene crucial for further investigation by the police. To prevent or minimise the destruction or obscuration of the trace evidence, the operator may switch the mobile platform to the mode of backtracking along the route of entry.

This has been solved by equipping the mobile platform with an autonomous navigation module which records the route and enables backtracking automatically, without any interaction from the operator.

2. AUTONOMIC OPERATION SCENARIO OF THE MOBILE PLATFORM

As mentioned above, the mobile platform has been equipped with an autonomous navigation module to enable autonomic operation. The entire hardware of the mobile platform is modular, which facilitates refitting to specific forensic investigation stages of the police forensic team aided by the mobile platform. If the mobile platform operator deems that a particular mission requires autonomous navigation, the module is fitted. This is usually the case in the initial missions during which the operator suspects a risk of RF communication loss and in missions that require minimising the risk of destroying trace evidence on the scene floor.

In the first scenario, the mobile platform enters indoor spaces under the remote RF control of the operator. The mobile platform saves its route to the onboard computer memory.

If the RF communication (and control) is lost, the mobile platform will stop moving at once. If the RF connection is not restored before a predefined timeout, the platform will start backtracking along the memorized route until the RF communication with the operator is re-established.

In the second scenario, the mobile platform is controlled remotely by the operator who conducts forensic tasks on the scene. If the operator deems it is necessary to have the mobile platform backtrack, they switch to the corresponding work mode. The mobile platform will autonomously backtrack along the memorized route for as long as the operator wants it to.

3. NAVIGATION SYSTEM

3.1. Mobile platform and the onboard computer

The mobile platform used in this research is a small-frame Mobot unit (see Fig. 1). The Mobot has four electric motors and a microcontroller unit. The microcontroller is tasked with low-level control of the motors with PID controllers. The onboard computer of the mobile platform is an industrial-grade unit type PC-104 with an Intel Atom 1 GHz CPU. The unit features sensor connection ports, a Wi-Fi interface card and a RF modem for wireless communication with the base station of the mobile platform. The onboard computer has a Linux-based operating system for the mobile platform control application. The control application receives and processes the sensor outputs, handles the communication with the base station, outputs the control commands for the mobile platform, and saves the mobile platform work parameters to file.

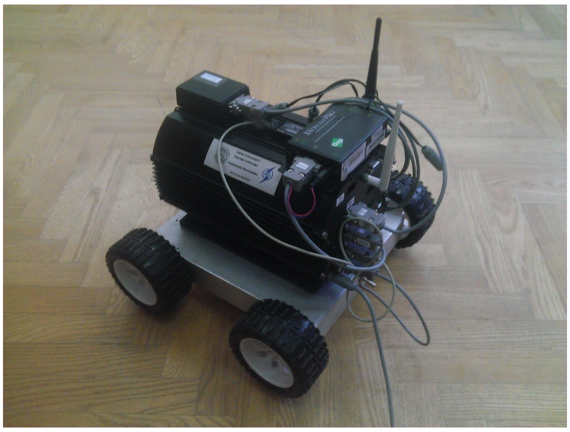

Fig. 1. The mobile platform with the onboard computer and essential sensors installed

3.2. Sensors

The navigation system contemplated herein is based on three sensors: an IMU (a Microstrain GX-3 Inertial Measurement Unit), a magnetic compass (HMR3500), and encoders in the motors of the mobile platform wheels. In its target version, the mobile platform system presented here will be capable of automatic return by guidance with the data from a video navigation system. It was possible to verify the mobile platform control algorithm performance, the onboard computer to platform connections and the onboard computer and sensor data exchange without the video navigation system. This sensor-based navigation system will be aiding the target solution, i.e. the main video navigation system.

The GX-3 IMU enables recording the measured angular speed and linear acceleration values. The measurements allow determining the spatial orientation and position of the mobile platform. The GX-3 IMU's main input for the control algorithm is the measurement of the angle on the vertical axis.

The HMR3500 magnetic compass enables measuring the spatial orientation of the mobile platform relative to the magnetic field lines. The encoder outputs, when processed accordingly, enable measuring the rotational speed of the mobile platform wheels. In this system, one full turn of a wheel is 72 output pulses of its encoder. With the wheel radius and the layout and position dimensions of the mobile platform wheels known, it is possible to calculate the heading and position of the platform with the encoder outputs.

3.3. Integration of systems

To have the navigation functions perform effectively, it is essential to provide the control system with the position and spatial orientation of the mobile platform. The presented system is assumed with the mobile platform moving on a horizontal plane. Hence the mobile platform position is determined in a two-dimensional system, and the heading is computed within a reference system related to the initial position of the mobile platform.

The navigational data of high quality is determined with the output data from several sensors. The mobile platform's heading is calculated with the data outputs of the mobile platform's gyroscopes and the magnetic compass. The data outputs are fused by a complementary filter. The data outputs from the accelerometers and gyroscopes are used to record the data on the pitch and roll of the mobile platform. These data outputs are not directly applied in the navigation and control functions; still, they can be relevant to the operator by providing information on the current orientation of the mobile platform. Fig. 2 shows a diagram of the sensor integration system.

The heading output calculated by a system of the IMU and a magnetometer is then used to determine the position of the mobile platform.

The data of the forward speed of the mobile platform is read from the outputs of the wheel encoder measurements. The forward speed value is then integrated to produce the actual position of the mobile platform.

This design of the navigation system uses one of the best characteristics of the installed sensors [5]. The IMU coupled with the magnetometer determines the heading of the mobile platform. The wheel encoder outputs serve to calculate the linear displacement of the mobile platform, which is a reliable measurement if no wheel slip is assumed.

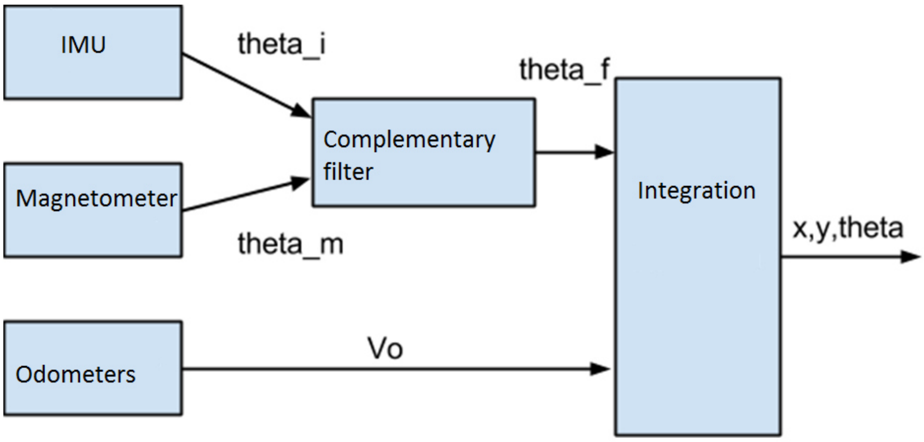

Fig. 2. Diagram of the navigational data integrating system

4. CONTROL ALGORITHM AND SIMULATION TEST RESULTS

4.1. The control algorithm

The nature of work of the mobile platform for the application presented herein does not require high speeds of motion. Hence the driving speed of the mobile platform was restricted to 60% of the maximum. This has ensured an improved safety level during the control algorithm testing. A reduced speed of the mobile platform helps with gathering more data, and this has facilitated recording the route. The wheel motor controls are coupled in pairs, i.e. a pair of left-hand wheels and a pair of right-hand wheels. A PWM signal governs the changes of the wheel rotational speed. The upper limit values are the maximum wheel motor speed. The first stage of development of the control system was to produce an algorithm that allowed movement on a route along a set heading. A detailed description of the control algorithm operation is shown in [1].

The control signal value E is calculated from the heading deviation, which is a difference between the actual heading determined by the sensors and the set heading. The heading deviation value is boosted with a proportional controller [2]. The integrated speed on axis Z in the control algorithm provides an approximate actual heading. The *E* error is calculated from the formula (1):

$$E = K_2(\theta_{given} - \theta_{actual}) \tag{1}$$

where:

E is the control signal;

K_2 is the proportional controller factor;

θ_{given} is the set heading;

θ_{actual} is the actual heading.

The mobile platform begins to turn when the control signal value *E* exceeds the value *M* (which is a setpoint input by the operator). Otherwise the mobile platform continues to move at maximum speed.

The mobile platform can turn in either of two modes: aggressive or gentle. The turn mode is selected depending on the turn sensitivity parameter *K*. It is a limit value which, when exceeded, forces the mobile platform to turn aggressively. The aggressive turn mode is enabled when the value *E* is higher than the value *K*. The wheel speed is set to maximum, and the wheel pairs start to rotate in opposite directions. An aggressive turn is made by the mobile platform altering its heading by virtually turning on the spot.

If the heading deviation is less than the turn sensitivity parameter *K* and more than *M*, the control algorithm will gradually reduce the rotational speed of the required wheel pair. The sense of rotation is identical in both wheel pairs. This gentle turn mode ensures a smooth transition to the set heading.

4.2. Driving via waypoints

The route to be covered by the mobile platform is a set of waypoints. The mobile platform follows the route by driving to successive waypoints. The waypoints are defined with sets of coordinates in the reference system related to the initial point of the mobile platform. The heading set for a waypoint is calculated from the difference between the actual position and the waypoint position according to this formula:

$$\theta_z = \operatorname{atan}\left(\frac{y_r - y_p}{x_r - x_p}\right) \tag{2}$$

where:

x_r, y_r are the mobile platform's actual position;

x_p, y_p are the coordinates of the set waypoint.

This set heading is an input parameter for the control algorithm discussed in the previous section. The control algorithm allows adjusting the tolerance for reaching a specific waypoint position by modifying the diameter of a circle centred on the waypoint. Once the mobile platform has entered a waypoint tolerance ring, the waypoint is quantified as reached. The waypoint tolerance ring was set at 0.1 [m] during the tests discussed herein.

The return route of the discussed application solution is set as a text file containing successive waypoints. In the target solution, the mobile platform navigating the route in the manual mode (i.e. controlled by the operator) will save the route covered. If autonomous return is forced, the control algorithm will load the saved route and execute the return. It is also possible to define the route lengths determined with other references than waypoints. A route length can be determined with a heading and a distance covered with that heading. A pause in driving may also be set by defining a time for which the mobile platform should be parked in a specific location.

Fig. 3 shows the control system architecture. It is a system comprising two closed loops, an external one and an internal one [3]. The external (master) loop is an algorithm for driving along a set route. The inner loop is a system for driving with a set heading. The low-level motor control system belongs to the Robot block, not shown in the diagram.

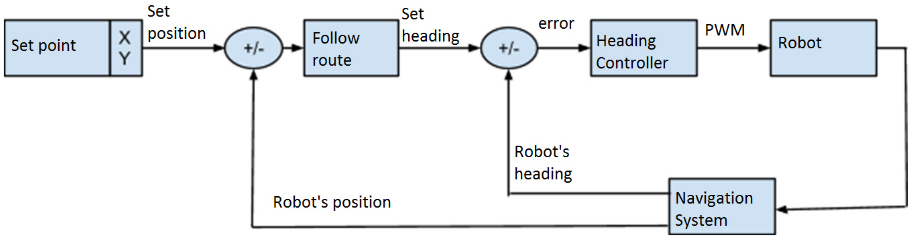

Fig. 3. System architecture

5. RESULTS OF MOBILE PLATFORM TESTING

The control algorithm presented above has been tested in two cases. Both drives to be carried out by the mobile platform consisted in driving along set waypoints to a destination and autonomous return along the route. The return part was executed not with the mobile platform turning around, but by backtracking in reverse. This functionality was forced by the application of video navigation in the target version of the navigation and control system. Turning the mobile platform around at its destination would result in images from the drive to the destination being completely different from those from the backtrack drive.

5.1. Test drive one: the horseshoe

The first test drive of the control algorithm was done over a route comprising three straight-line lengths arranged to form a C-section. The driving trajectory was determined with 4 waypoints, shown with green circles in Fig. 4. The mobile platform drove along the route from a start point with the coordinates [0, 0] to the destination with the coordinates [1, 0]. Having reached this destination, the mobile platform returned autonomously. The chart shows that all route waypoints were reached within the set tolerance, shown by the green circles.

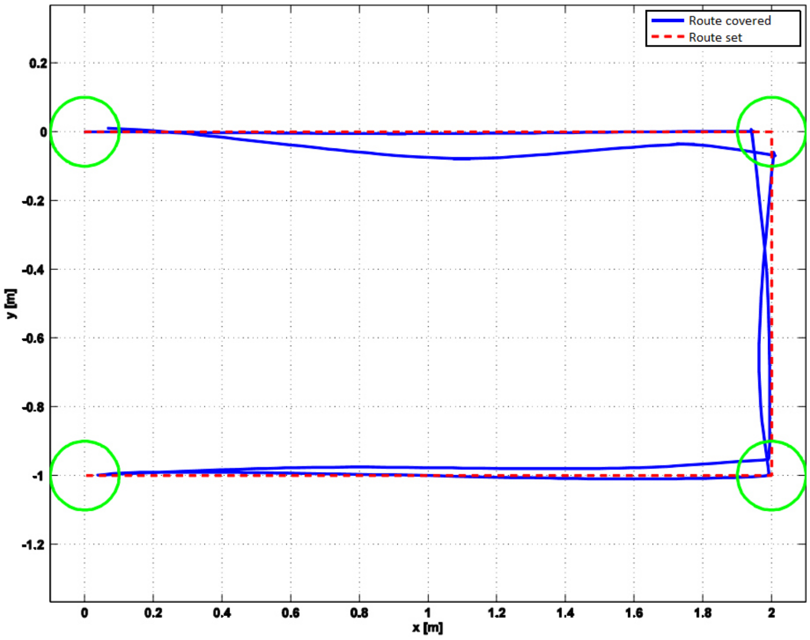

Fig. 4. Test drive one

Fig. 5 shows a chart of the wheel rotational speed control signal and the rotational speed values recorded with the encoders. The chart shows that the control system response is fast (below 1 second), although the wheels in motion reveal slight oscillations, most likely caused by measurement signal noise.

Fig. 5 shows the two turn modes discussed in Section 4.1. An aggressive turn is shown between the seconds 35 and 45 on the chart. In this period, the control signal forced a speed reduction of the right-hand wheel pair twice to -60 [rps], while maintaining the maximum speed of the left-hand wheel pair at 60 [rps]. The differential speed of the two wheel pairs is at its maximum, and theoretically, the mobile platform turns in place.

Between the seconds 57 and 65 there are also two aggressive turns when backtracking. Following the end of the aggressive turn (where the green signal curve reaches -60 [rps]), a gentle turn is seen. The speed control signal value for the left-hand wheel pair rose from -60 [rps] to -20 [rps]. In a similar fashion, the mobile platform turns gently just before the aggressive turn at the 63rd second.

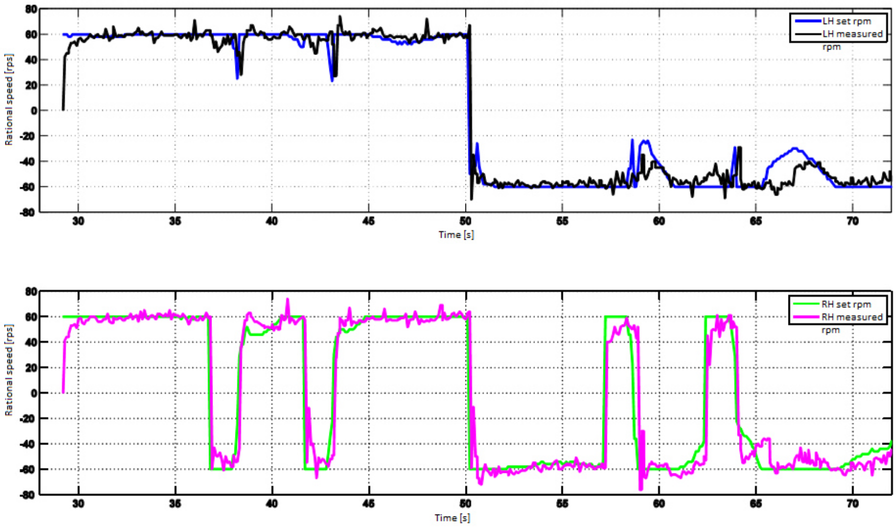

Fig. 5. Wheel speed control values (set and measured): left-hand wheels in the top chart; right-hand wheels in the bottom chart

5.2. Test drive two: entering a room

The second test simulated the target operating environment of the mobile platform. The platform was to enter a room through a doorway and return to its start point by backtracking the route of entry. Fig.6 shows a route record from the test. It is evident that the mobile platform managed to follow the preset route correctly and backtracked from the room precisely along it. Since the application has no active obstacle detection system, it is essential to precisely map the route. This will avoid collisions with indoor objects.

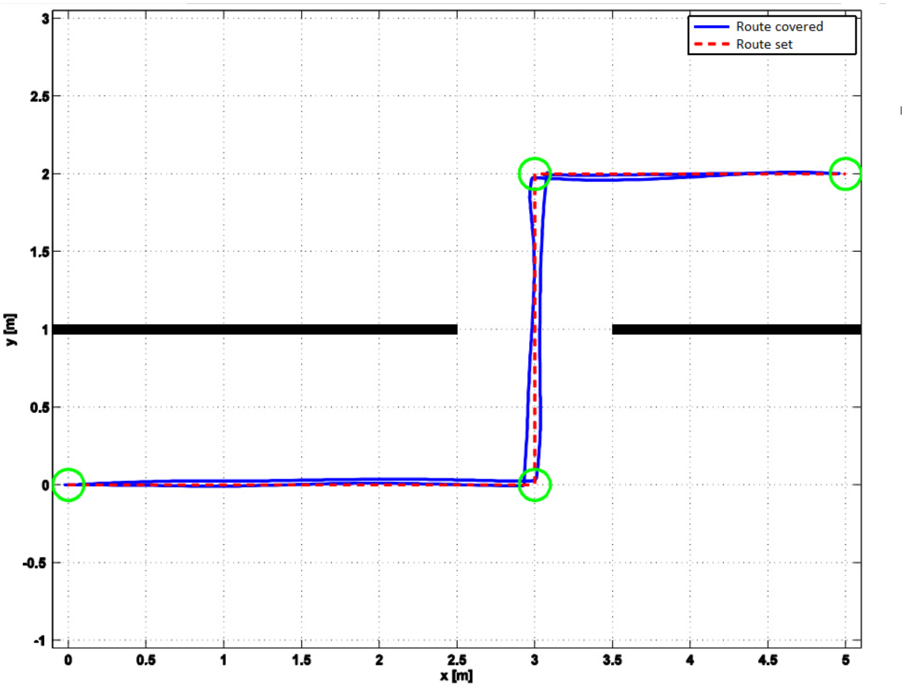

Fig. 6. Test drive two: driving from a hallway into a room

6. SUMMARY

The work presented in this paper is a part of the tasks performed under a project titled „Design of a mobile platform for the support of forensic testing of scenes with potential CBRN hazards". The objective of the subtask presented herein was to verify the operation of a control algorithm that enables the mobile platform to follow a preset heading. The results presented here were intended first to verify the correct performance of the control algorithm and integration of data from individual sensors. The control algorithm and the mobile platform performance were stable and ensured repeatability of the routes presented herein. Further work will require testing of a module designed for more complex trajectories and longer routes, and the more unusual manoeuvres the mobile system operator may attempt. The tests presented herein have confirmed the correct performance of the system as a whole and its components. These results have enabled the commencement of the last stage of the project – integration of the mobile platform system with a video camera, to form the master navigation system.

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System nawigacji i sterowania dla robota mobilnego patrolującego budynki

Robert GŁĘBOCKI, Paweł KICMAN, Antoni KOPYT

Politechnika Warszawska, Wydział Mechaniczny Energetyki i Lotnictwa,
ul. Nowowiejska 24, 00-665 Warszawa

Streszczenie. Artykuł prezentuje prace wykonane w ramach projektu badawczego „Zaprojektowanie mobilnej platformy do wsparcia badań kryminalistycznych miejsc zdarzeń, w których może występować zagrożenie CBRN”. W artykule przedstawiono sposób działania algorytmu sterowania platformą, wyznaczania pozycji oraz przygotowanie systemu do integracji z nawigacją wizyjną. Czujniki, jakie zostały zamontowane na platformie, mają służyć za systemy awaryjne w razie utraty łączności pomiędzy platformą a operatorem. W artykule przedstawione zostały wyniki z przejazdów próbnych weryfikujących działanie algorytmu.

Słowa kluczowe: robotyka, robot mobilny, sterowanie, fuzja danych