Simulation and Modeling of Fire Searching Using a Mobile Robot in Low Visibility Conditions

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***Abstract*-This paper presents an approach to search for a fire source in a group of rooms using a mobile tracked reconnaissance robot. The approach is based on the proportional guidance method in a temperature field. This method integrates robot kinematic and dynamic equations. According to the control strategy, a robot angular velocity is proportional to the rate of turn of the temperature gradient that guides the robot to the fire. We prove that the passive proportional guidance method is equivalent to the gradient-search method. The navigation law is simulated and tested experimentally using the tracked robot in the case of a temperature field.**

Keywords- Proportional Navigation; Search for Source of Fire Using Mobile Robot; Exploration of Fire

I. INTRODUCTION

The problem of fire reconnaissance is a topical issue today. One of the particular tasks involved in such reconnaissance is the searching for a fire in a group of rooms in low visibility conditions. Given the large scale of a building, for example, warehouse, the low visibility and time constraints render the searching of a warehouse very risky. The velocity of goal seeking for fire is less than 5 meters per minute [1]. A decrease of risk facing the fire-fighter is attained through the use of mobile robots. The smoke obstructs perception in the visible spectrum: this is the case for the human eye as well as for most robotic sensors such as cameras (mono or stereo) but also for laser range finders (LRF) [2, 3]. Therefore, we have solved the problem of searching for the fire using fields of fire hazards, which in our case is the temperature field.

The purpose of this paper, which extends our earlier work [4], is to show the efficiency of navigation law based on the proportional navigation method both theoretically and experimentally taking into account the dynamics of a robot.

The proportional navigation guidance law is a navigation method which is well-known and has been widely discussed in the aerospace community. Also, this method has recently been used for navigation problems facing wheeled mobile robots [3, 6]. In the paper [6] the navigation method is shown in a canonic form only for a kinematic robotic model and a visible target. We have based our work on the results of the paper [3], in which the target was an odor source and invisible. The authors of the paper [3] designed their method using bilateral comparison. We will show that this method is equivalent to the proportional guidance method in canonic form.

The paper is organized as follows. In Section II, we discuss equations of proportional navigation method and its features while searching for the source of the fire. In Section III, we present simulation results of the robot navigation in a dynamic case. In Section IV, we discuss modeling results of the robotic navigation and compare them with simulation results.

II. PROPORTIONAL NAVIGATION METHOD

The robot is assumed to have two measuring systems used for navigation [3]: one of them is the bilateral system (differential temperature channel) and another one is the system of measuring temperature at a point *A*. As opposed to decisions made by the authors of paper [3] we have used temperature sensors instead of odor concentration sensors as the former ones are more suitable for fire conditions.

Where the temperature direction gradient is given by the angle $\varphi(\mathbf{r},t)$ with an orientation along an ascending gradient means (see Fig.1), then Expression (1) is valid in the global frame *OXY*:

$$\varphi(\mathbf{r},t) = \theta(t) + \eta(t)\,. \tag{1}$$

Since a target point is fixed, kinematic guidance equations containing the Expression (1) have a form (2), as, for example, the equations in the paper [5]:

$$\begin{cases} \dfrac{dr}{dt} = -\upsilon\cos(\varphi-\theta) \\ r\dfrac{d\varphi}{dt} = \upsilon\sin(\varphi-\theta) \end{cases}, \tag{2}$$

where, r – the module of a radius-vector $\mathbf{r}$ (a distance between the target point P and the origin of the moving frame Axy, υ – the linear velocity of robot.

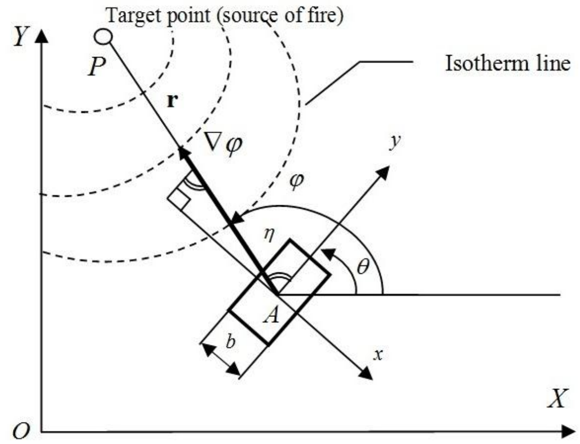


Fig. 1 Frames for the proportional navigation method: *OXY* – the global frame, *Axy* – the moving frame, $\mathbf{r}$ – the radius-vector of the point P, θ – the angle of robot rotation in the global frame, η – the lead angle, $\nabla\varphi$ – the temperature gradient, φ – the angle of temperature direction gradient, b – the distance between sensors of the differential temperature channel

Differentiating (1) with respect to time, we get the following evaluation for the rate of the lead angle change:

$$\frac{d\eta}{dt} = \upsilon \cdot \mathbf{u}(\theta) \cdot \nabla\varphi - \omega + \frac{\partial\varphi}{\partial t}, \tag{3}$$

where, $\nabla\varphi$ – the temperature gradient at the point A in the direction of angle φ, ω – the angular velocity of robot, $\mathbf{u}(\theta)$ – the unit vector of OX axis, $\partial\varphi/\partial t$ – a variation of temperature field.

We would like to stress that AP is a sight line. From Expressions (2) and (3) the rotating velocity of the sight line AP is determined as:

$$\frac{d\varphi}{dt} = \frac{\upsilon \sin\eta}{r} = \upsilon \cdot \mathbf{u}(\theta) \cdot \nabla\varphi + \frac{\partial\varphi}{\partial t}.$$

A kinematic ratio determining the guidance law is required to be added for the condition of the robot guidance to the point P for full filling. This condition may be denoted as $r = \frac{2K\upsilon \sin\eta}{\omega}$ [3]. Thus,

$$\omega = \frac{2K\upsilon \sin\eta}{r}, or\ \omega = K_{\mathrm{H}} \cdot \dot{\varphi} = K_{\mathrm{H}} \cdot \frac{d\varphi}{dt}, \tag{4}$$

$K_{\mathrm{H}}=2K$ – the coefficient of the proportional guidance ($K>0$). In this case, the proportional guidance law is determined in the normal form: a robot angular velocity is proportional to the sightline turn rate.

On the other hand, the ratio of the Expression (4) with the gradient method in the case of continuous movement should be mentioned. The robot moves in a temperature field in a direction close to the instantaneous direction of the gradient. Therefore, the robot's angular velocity is proportional to the rate of turn of the temperature gradient, and the proportional guidance method is mathematically equivalent to the gradient-search method. The continuous gradient-search method is known to be stable, that is, the robot enters a neighbourhood around an extremum for any starts point.

The temperature distribution $T(r)$ in the point A with the distance $r=AP$ (P – doorway or fire) is determined by relevant jet flow law as the next expression indicates [7]:

$$T(r) = T_0 + \frac{\left(T_{o.m} - T_0\right) \cdot H^{0.62}}{\left(H + r\right)^{0.62}}, \tag{5}$$

where T_0 – the temperature in the start-point of a robot, $T_{o.m.}$ – the temperature in a doorway, H – a headroom.

When lateral temperatures (temperatures along the sides of the robot chassis) are not too different the measured differential temperature is $\Delta T \approx -b \cdot \left|\frac{dT}{dr}(r)\right| \sin\eta$, here $\frac{dT}{dr}(r)$ is the consequence from the Expression (5): $\frac{dT}{dr}(r) = -\frac{0.62}{r+H}\left(T(r) - T_0\right)$.

Substituting these expressions in (4) and assuming that $\frac{dT}{dr}=\frac{1}{\upsilon}\cdot\frac{dT}{dt}=\frac{1}{\upsilon}\cdot\dot{T}$, the Expression (4) with regard (5) can be written in the form (6):

$$\omega=\frac{K_{\mathrm{H}}\cdot\upsilon^2\cdot\Delta T}{b\cdot\left(0.62\cdot\left(T(r)-T_0\right)\cdot\upsilon+H\cdot\dot{T}\right)}, \tag{6}$$

where $\dot{T}$ – the temperature change over time, and the rotating velocity of the sight line is $\dot{\varphi}=\frac{\upsilon^2\cdot\Delta T}{b\cdot\left(0.62\cdot\left(T(r)-T_0\right)\cdot\upsilon+H\cdot\dot{T}\right)}$. Therefore, the Equation (6) is the angular velocity, which depends on the location of temperature sensors and is characteristic of a scalar temperature field.

The minimum value of the kinematic coefficient K_H for a trajectory with an aperiodic character is determined by the next expression and depends on the values of $\eta_{\max}$, $r_{\min}$, υ and $\omega_{\max}$:

$$K_H=\frac{r_{\min}\cdot\omega_{\max}}{2\upsilon\cdot\sin\eta_{\max}},$$

where $\eta_{\max}$ – a maximum value of lead, $r_{\min}$ – minimum distance of guidance, $\omega_{\max}$ – a maximum permissible angle velocity.

When we take into account the dynamics of the measurement system and the robotic platform, the K_H will differ from its kinematic value. As it follows from Equation (6) there is a non-stable point at the moment when the robot starts moving. The modification of the navigation law (6) is used for trajectory stabilization. There are two methods for this. The first method is to add a small quantity ε in the calculation $(T(r)-T_0)$, where physically ε is a dynamic error of the temperature measurement. This method is illustrated by the Expression (7):

$$\omega=\frac{K_{\mathrm{H}}\cdot\upsilon^2\cdot\Delta T}{b\cdot\left(0.62\cdot\left(T(r)-T_0+\varepsilon\right)\cdot\upsilon+H\cdot\dot{T}\right)}, \tag{7}$$

The second method is to disable the control loop for a small period of time, when the robot starts moving. Both methods require the consideration of the robot's dynamics to select the proportional coefficient K_H. The main features of the first method will be considered in Section III.

III. SIMULATIONS RESULTS

The simulation of the fire searching process using a mobile robot has been performed in Matlab and MBTY (which is now called SimInTech) [8]. A simulation model in block diagram form consists of the following parts: a kinematic robotic model, a dynamic robotic model, a dynamic measurement system model, the temperature field model (5) and an evaluation unit of $\frac{d\varphi}{dt}$. The simulation model in an expanded form is given in our previous paper [5]. The numerical data used in the simulation for the robot model described in Section IV is as follows: the mass of robot (m=1.26 kg), the track width of robot (B=0.105 m), the coordinate of centre of mass along the longitudinal axis relative to geometric centre of robotic chassis a=0.047 m, the radius of driving wheel r_{wheel}=0.023 m, the linear velocity υ=0,13 m/s, the maximum angle value $\omega_{\max}$=0.5 s^{-1}, the time constant of linear velocity channel $T_\upsilon=0.07\,\mathrm{s}$, the time constant of angular velocity channel $T_\Omega=0.13\,\mathrm{s}$, the gain of linear velocity channel $K_\upsilon=0.038\,\mathrm{m}\cdot(\mathrm{V}\cdot\mathrm{s})^{-1}$, the gain of disturbance in the angular velocity channel $K_\Omega=0.72(\mathrm{V}\cdot\mathrm{s})^{-1}$, gains of disturbance in the linear velocity channel $K_{f\upsilon}=0.055$ and the angular velocity channel $K_{f\Omega}=20$ respectively, the moment of inertia relative to a vertical axis of the robot J=0.006 kg·m^3, the moment of a resistance to rotation depending on its radius $M_C=0.023\cdot\mu(R)$ N·m (R is a radius of the rotation), the time constant of measuring temperature systems T=3 s including filters.

The first step of simulation was to investigate the influence of model parameters on the selection of K_H. Simulation results for various K_H, r_{min}= 5 m, η_0= 1 rad, ε=1 and the continuous model are shown in Fig. 2.

It should be mentioned that the robot misses the target of less than 0.1 meter and the coefficient K_H defines the line along which the trajectory is stabilized. Actually, this line is one of the collection of horizontal and longitudinal axes. Also, Fig. 2 shows that there is a relation between the K_H and temperature field characteristics.

Simulation results (Fig. 3) indicate the weak dependence of trajectories on a module of temperature field gradient when the simulation model is continuous. Thus, K_H can be a constant for such a model type.

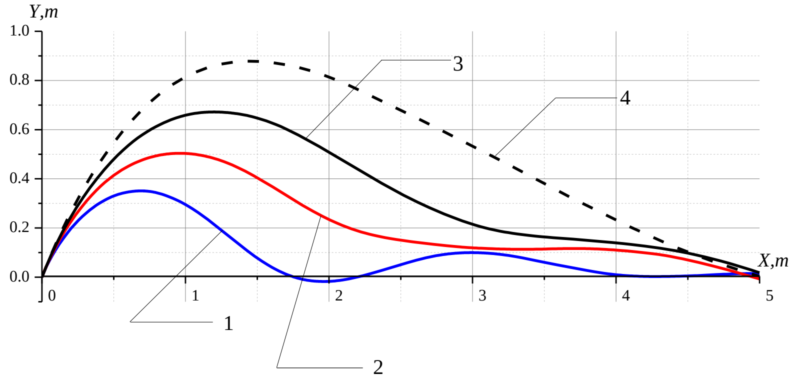


Fig. 2 Simulation trajectories of the robot in the continuous model (ε =1): 1 – K_H=30, 2 – K_H =20, 3 – K_H=15, 4 – K_H=10

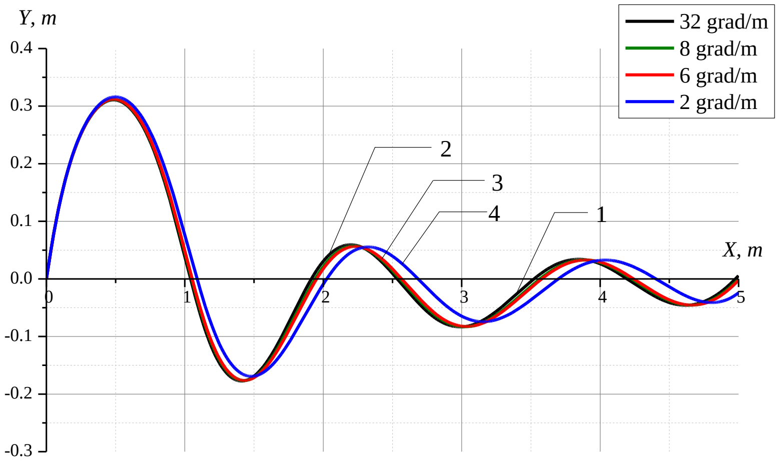


Fig. 3 Trajectories of the robot with K_H=50 and with varying temperature gradient values dT/dr (ε=1): 1 – 32°/m; 2 – 8°/m; 3 – 6°/m; 4 – 2°/m

The influence of the module of temperature gradient is more complicated in a discrete model. So, if the sampling period of time is Δt = 0.02 s and the amplitude quantization of temperature channel is 0.1°C (in our case the A/D convertor (ADC) capacity was 10 bit and ε=1), the robot trajectory motion strongly depends on the module of temperature gradient (Fig. 4) with the constant coefficient K_H.

The stabilization of the trajectory is observed for the various longitudinal axes. The situation becomes even more complicated for the analytic analysis when the amplitude quantization period in the differential channel temperature measurement is added to the model (Fig. 5). In such a case trajectories differ a lot from those of the continuous case, when the module of the temperature gradient is less than 10 °/m, and for small gradient values the motion is unstable (see Graphic 4 in Fig. 5). Thus, we can draw the conclusion that the measurement system should be continuous and the initial segment of trajectory is the most interesting aspect for our investigation.

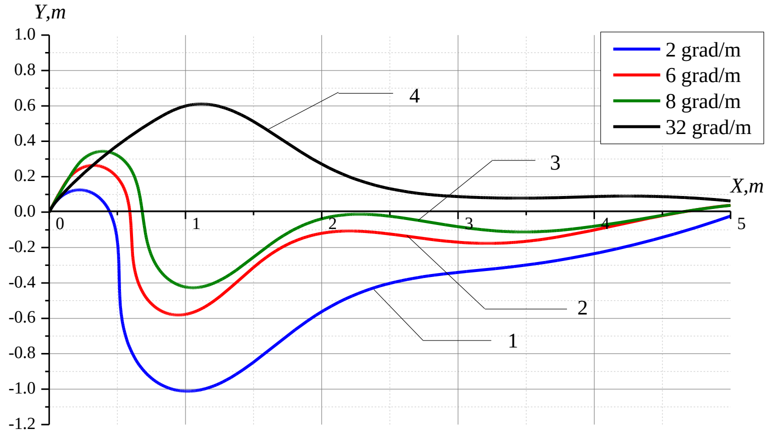


Fig. 4 Trajectories of the robot with K_H=6 and with varying temperature gradient values dT/dr , using the sampling period of time Δt = 0.02 s, the amplitude quantization in the temperature channel is 0.1°C (ε=1): 1 – 2°/m; 2 – 6°/m; 3 – 8°/m; 4 – 32°/m

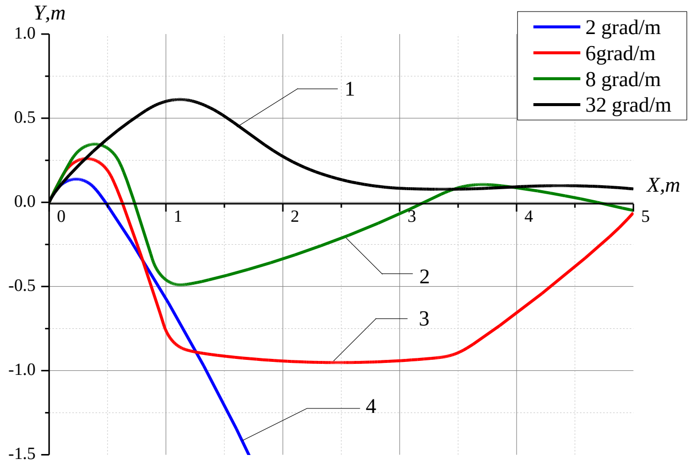


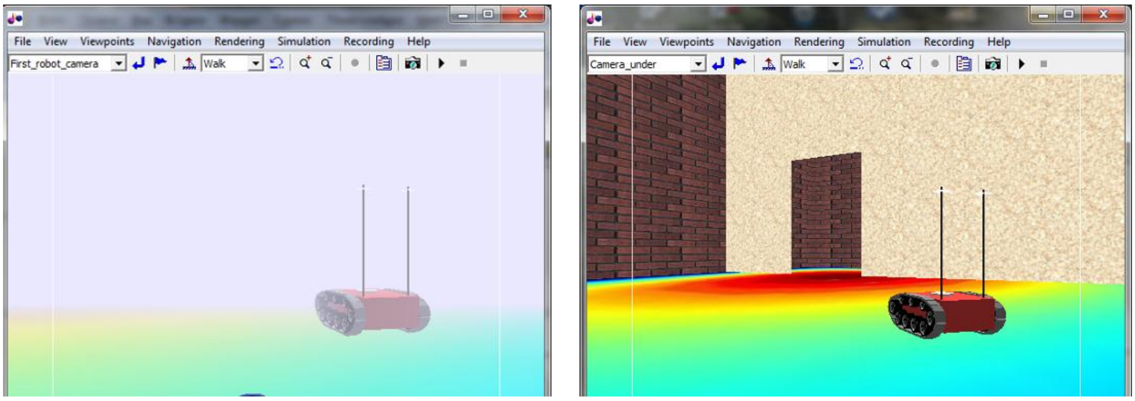
Fig. 5 Trajectories of the robot with K_H=6 and with varying temperature gradient values dT/dr, using the sampling period of time Δt = 0.02 s and the amplitude quantization in the temperature channel is 0.1°C. The amplitude quantization in the differential temperature channel is 0.037°C (ε=1): 1 – 32°/m; 2 – 8°/m; 3 – 6°/m; 4 – 2°/m

The second step of the simulation was to investigate the navigation law in Matlab, when the fire model is more complicated than the Expression (5). The simulation was carried out using Simulink3D for the visualization of the robot's motion. A real fire is a complex time-dependent physical phenomenon and its simulation using the Navier-Stocks equations requires a large amount of computational time. Therefore, the heat equation without convective term of the general equation of hydrodynamics has been used:

$$\rho c_v \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + S(x,y), \; S(x,y) = T_0 \cdot e^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2} \right)}$$

The robot's motion is simulated in the virtual space room with dimensions 5m x 5m x 3m with two doors made in Simulink3D. Combustion products flowed into the next room through one of these doors (Fig. 6). So, this door was a heat source *S(x,y)*. The quasi-stationary process was assumed to be a constant ($\rho c_v \approx const$) and the heat distribution was considered to be permanent for 5-10 seconds. This assumption allowed us to set the two-dimensional temperature field as files containing tables and to update them at intervals during the simulation process. The variation $\partial\varphi/\partial t$ of the temperature field was set as an additive Gaussian noise with the dispersion $\sigma_x^2 = \sigma_y^2 = 2$ ℃. The angle velocity was limited by the following range $[-0.5;0.5]$ rad/s. The projection of temperature field was made on a floor for the sake of clarity.

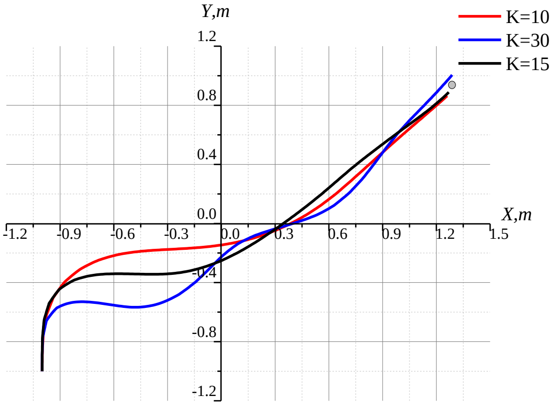
Simulink3D Animation Toolbox provides an excellent opportunity to control the robot manually via a control panel of VRML-browser. We manually tested the element of control when there was a smoke in the visual scene (Fig. 6a). If the operator did not know where the doorway was (Fig. 6b), the results of his search were held to be random.



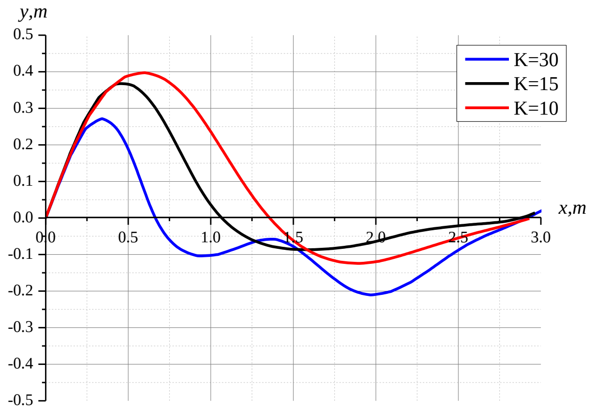
(a) (b)

Fig. 6 Visualization of the robot's motion in Simulink 3D: (a) – the simulation with smoke, (b) – the simulation without smoke

Some of simulation results of the continuous control system are shown in Fig. 7a. The initial distance between the robot and the target point was reduced to 3.0 m and η_0= 0.7 rad. These trajectories have the same behavior as trajectories in Fig. 2. Fig. 7b presents the same results as in Fig. 7a. The only difference is a rotation on η_0 for a better presentation.



(a)



(b)

Fig. 7 Simulation trajectories of the robot in a continuous model

The data shows that the navigation law works in the case of the quasi-stationary temperature field and the simulation model is verified. The next step of our investigations was to model the searching process of source fire in a test bench and to compare the results with the simulation results.

IV. MODELING RESULTS

The special test bench (Fig. 8) simulating a fire was used for physically-based modeling. The robot used in our experiments is shown in Fig. 8b. The control system of the robot was made on the basis of an Arduino circuit board. The temperature measurement system, consisting of two measurement channels, was constructed on the basis of K-type thermocouples having a circle polar pattern (Fig. 8b). The amplifying and normalization signals were implemented using operational amplifiers OP193 and OP196. The ADC capacity was 10 bit. The resolution of the bilateral temperature measurement channel was 0.037 ℃ and the temperature measurement channel at point *A* had a resolution was 0.1 ℃. The control system of the mobile robot was divided into two levels: an executive and a tactical. The first level was designed for providing the stabilization of angular velocity and primary processing of measurement data, the second was responsible for data acquisition and the evaluation of required angular velocity. The communication between these levels was realized via XBee modules. The software for the executive level was written in C++ and the software for the tactical level was written in G-language in LabVIEW. A decomposition of the control system on two levels has been made for the future use of fuzzy logic.

(a)

(b)

Fig. 8 The equipment for modeling: (a) – the test bench, (b) – the robot in the test bench

It should be noted that this robot is not equipped with video cameras, so low visibility conditions were reproduced. Therefore the searching of heat source simulating the fire is implemented using a robotic guidance system.

In order to compare physical modeling results with simulation results, the temperature field of the heat source was simulated in PyroSim (Fig. 9). So, firstly, we verified the Expression (5) and, the secondly, made sure that the projection of convection column of fire is not a point source of the temperature field (Fig. 9). Therefore, we have an imaginary target point [9]. To achieve a correct comparison between the modeling results and the simulation results, the distance between the robot and source of fire in the simulation process will be less than its measured value in modeling.

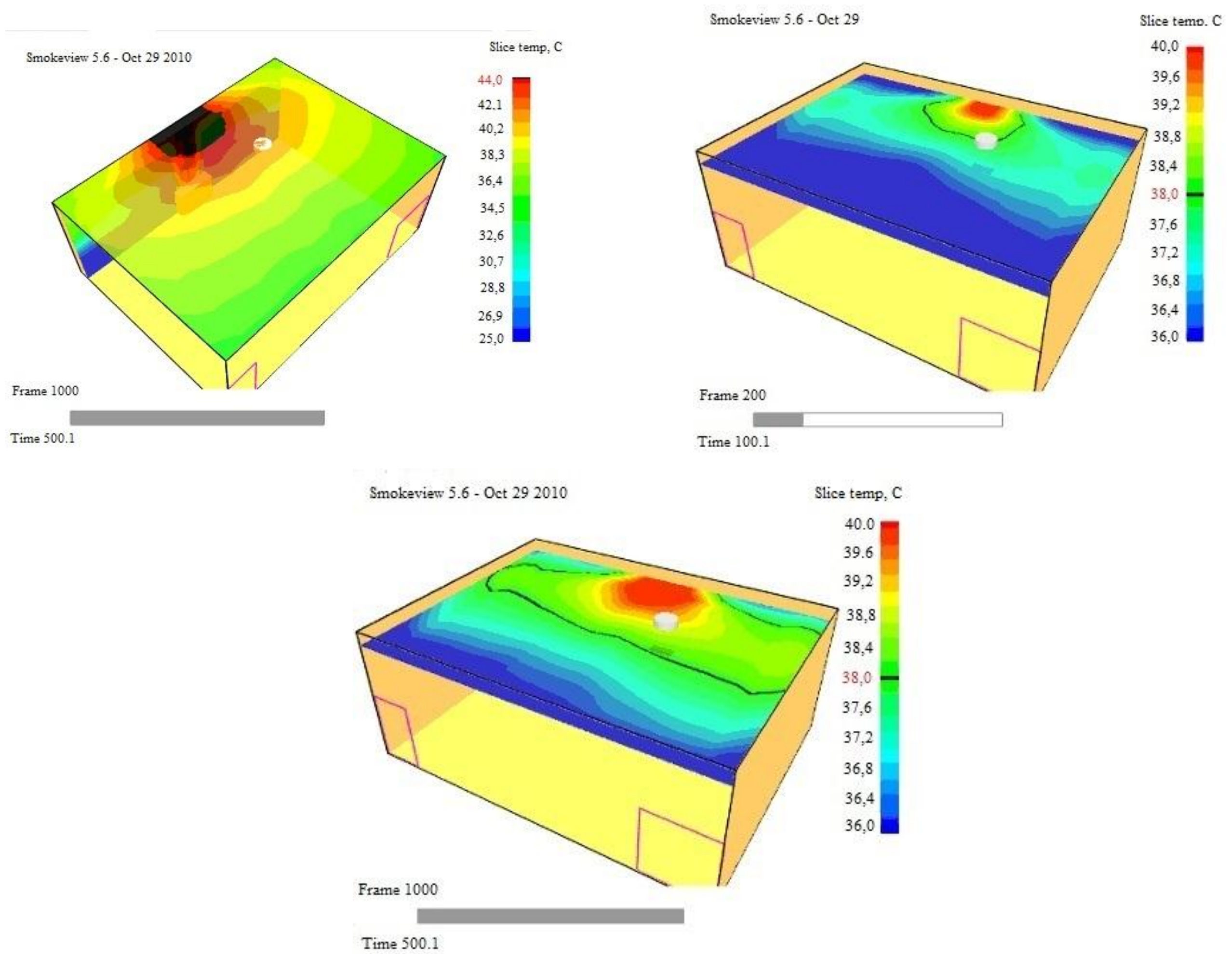


Fig. 9 Simulation results of the temperature field made in PyroSim for the test bench

The scheme of the experiment and overall dimensions are presented in Fig. 10, with the coefficient K_H in this experiment being 0.75.

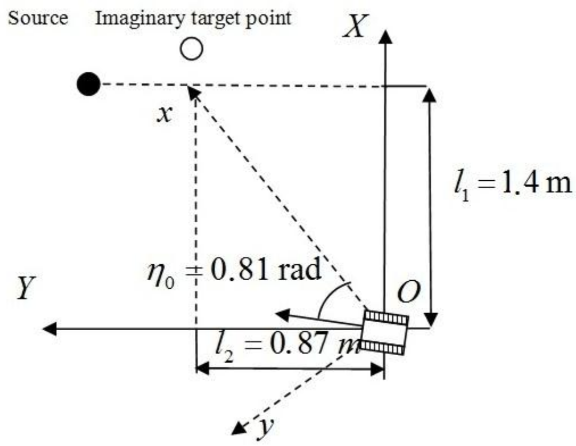


Fig. 10 The scheme of experiment

Stills of robot motion in the experiment are presented in Fig. 11. The measurement of angular velocity is shown in the Fig. 12a, and the comparison of the simulation results is presented in the Fig. 12b, with Graphic 1 denoting the real angular velocity of robot and Graphic 2 the evaluation of the measurement angular velocity in the simulation model.

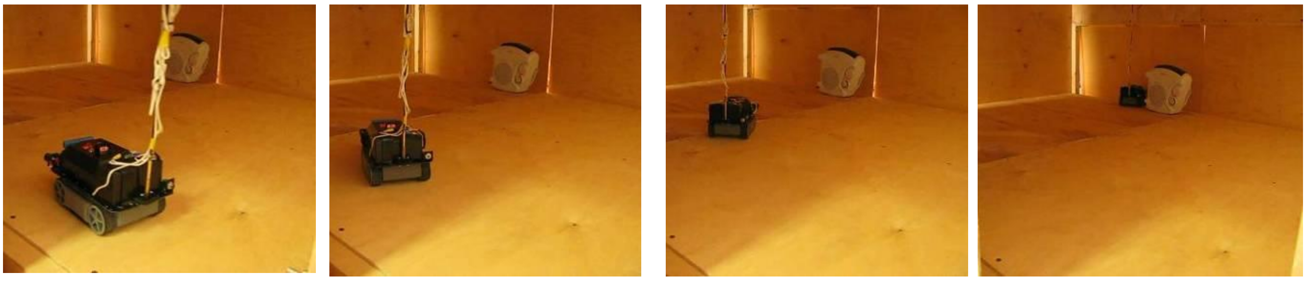


Fig.11. Stills of robot motion

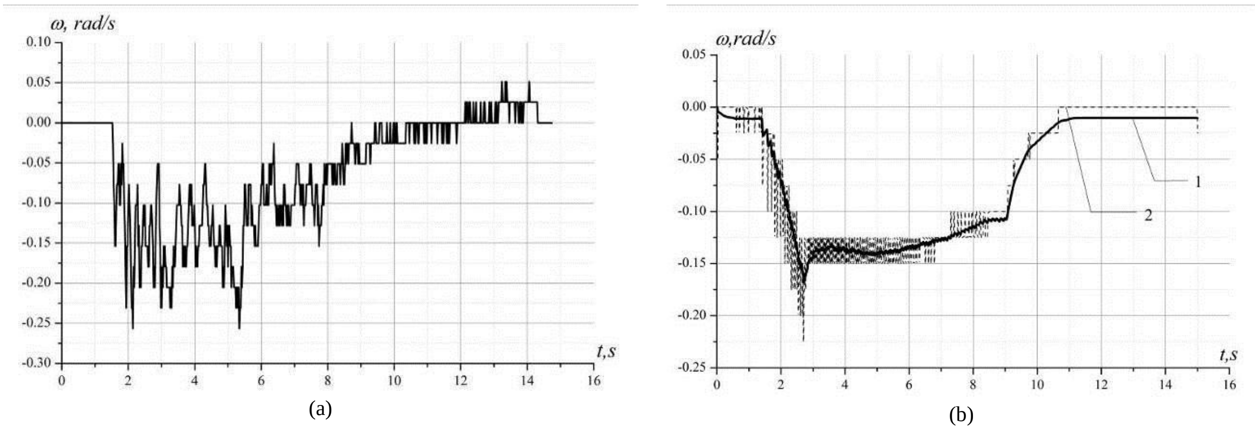


Fig. 12 The angular velocity of robot in modeling (a) and simulation (b): 1 – real angular velocity, 2 – measurement angular velocity

The comparison of results of simulation and modeling for the initial conditions of experiment are presented in Fig. 13.

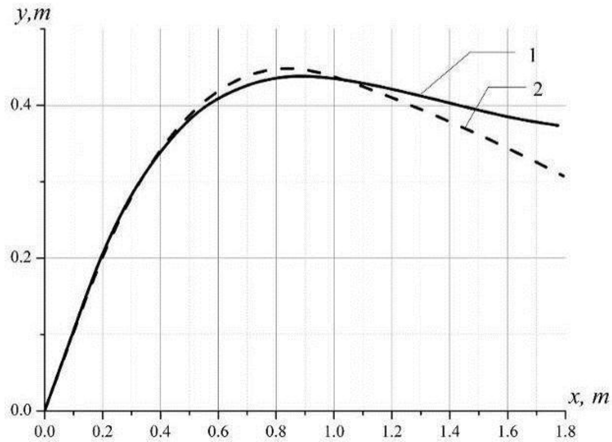


Fig. 13 Trajectories of robot (1 – simulation result, 2 – modeling result)

As we can see, the results are similar, with the divergence being less than 10%. The small value divergence confirmed proportional guidance model adequacy taking into account the dynamic characteristics of the robot and its measurement system. Within the modeling, 25 experiments have been conducted to search for the source for various initial conditions, and, in 20 cases maximum deviation of the robot from the target point was less than 0.2 m. So, we believe that the method of proportional robot guidance in the temperature field is applicable.

V. DISCUSSIONS AND CONCLUSIONS

This paper presents a fire searching method using temperature gradient. We have established a link between this method and proportional guidance originally used for tracking moving objects: an angle velocity of robot has to be proportional to the rate of change of direction of temperature gradient, which is determined by a bilateral temperature, a current temperature, a temperature change rate, the velocity of the robot and the headroom. An important difference between the proposed method and the classical proportional guidance method is to stabilize, not start, the final section of the trajectory of motion, so that, the control algorithm has a trajectory stabilization procedure.

But the proposed method is efficient only if there is a smooth temperature gradient. Part of the problem is solved by the use of low-pass filters in temperature channels and by the location of temperature sensors near the ceiling, but this solution has some technical problems and requires justification for the choice of the coefficient K_H and affects the robot's dynamics, especially in the discrete model as shown in Section III. In general, modeling results confirmed the efficiency of the developed method even with small fluctuations in the thermal field, which were clearly visible in the simulation in PyroSim.

Since in a real fire there is a significant heat flow turbulence, therefore, as a solution for high turbulent environment in future we will consider using the "Infotaxis" strategy [10, 11], which does not require a temperature gradient for searching a fire source. It should be mentioned that the use of this strategy is of considerable interest for dealing with problems encountered in the use of fire-fighting robotics.

REFERENCES

[1] J. Penders, L. Alboul, U. Witkowski, A. Naghshm, J. Saez-Pons, S. Herbrechtsmeier, and M. El-Habbal, "GUARDIANS final report part1(draft): a robot swarm assisting a human fire fighter", 2009. Available: http://shura.shu.ac.uk/1089/ 1/FinalReportPart1.pdf

[2] J. Pascoal, L. Marques, and A. de Almeida, "Assessment of laser range finders in risky environments". In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Nice, France, September 2008, pp. 3533-3538.

[3] E. Hugues, O. Rochel, and O. Martinez, Navigation strategies for a robot in a turbulent odor plume using bilateral comparison // Proceedings of the 11th International Conference on Advanced Robotics ICAR'2003, Coimbra, Portugal. pp. 381-386.

[4] R.D. Schraft, H. Rust, and H.R. Gehringer, "Sensors for the object detection in environments with high heat radiation and photoresist of diffuse visibility conditions", Experimental Robotics VI, The Sixth International Symposium, Sydney, Australia, March 26-29, 1999, pp.69-78.

[5] A.A. Tachkov, "Using the Proportional Guidance Method for Mobile Reconnaissance Robot Control in the Fire", Mechatronics, Automation and Controlling, iss. 7, 2012, pp. 27-33.

[6] F. Belkhouche and B. Belkhouche, "Wheeled mobile robot navigation using proportional navigation", Advanced Robotics, vol. 21, iss. 3-4, 2007, pp. 395-520.

[7] I.S. Molchadsky, "Fire in Structure" (in Russian), Moscow: VNIIPO, 2005, 456pp.

[8] 3V Swrvices, SimInTech (in Russian), http://3v-services.com/ru/

[9] D. Drysdale, "An Introduction in Fire Dynamics" – 2nd ed., 1999, 465 pp.

[10] Moraud E. M., and Martinez D. Effectiveness and robustness of robot infotaxis for searching in dilute conditions. Front. Neurorobotics, 2010, 4:1. doi: 10.3389/fnbot.2010.00001.

[11] M. Vergassola, E. Villermaux, and B.I. Shraiman, "Infotaxis as a strategy for searching without gradients", Nature, vol. 445 (25 January 2007), pp. 406-409.

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