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Sensor-Based Intelligent Navigation and Control of Autonomous Mobile Robots for Advanced Terrain Missions

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The paper regards sensor-based intelligent mobile robot navigation and control in the case of unknown environment in the presence of obstacles. The paper deals with combined, fuzzy and dynamic control of autonomous mobile robots and their motion in unknown environment with different obstacles. The control strategy and algorithms described in the paper are suitable for wireless sensor-based remote control of mobile robots motion in different scenarios and terrain missions of interest for advanced military and civil applications. A detailed mathematical model of a mobile robotic platform is given as well as a corresponding two-level hierarchical control system structure with a high-level cognitive block for intelligent navigation and a low-level control block intended for dynamic control and trajectory tracking. A detailed description of the proposed fuzzy inference system structure is presented in the paper. Some implementation aspects are described as well as experimental control verification.

Key words: **robots, robotized vehicle, obstacle avoidance, motion control, remote control, navigation, artificial intelligence, fuzzy inference system, mathematical model.**

Introduction

IN the last ten years investigation and development in the field of autonomous mobile robotic systems have been very intensive with a variety of examples of advanced applications. Nowadays, such advanced technical systems are ultimatively employed in different military applications. Mobile robots are combined with different kinds of sensors and integrated within wireless heterogeneous robot-sensor networks. Wireless Robot-Sensor Networked (WRSN) systems refer to multiple robots operating together in coordination or cooperatively with sensors, embedded computers, and human users [1]. The cooperation entails more than one entity working towards a common goal while the coordination implies a relationship between entities that ensures efficiency or harmony. Communication between entities is fundamental to both cooperation and coordination and hence the central role of the networked system. Embedded computers and sensors are now ubiquitous in contemporary military devices and equipment, and increasingly wireless ad-hoc networks or plug-and-play wired networks are becoming commonplace. Robots are functioning in environments while performing tasks that require them to coordinate with other robots, cooperate with humans, and act on information derived from multiple sensors. In many cases, these human users, robots and sensors are not collocated, and the coordination and communication happens through a network. Networked robots allow multiple robots and auxiliary entities to perform tasks that are well beyond the abilities of a single robot. Robots can automatically couple to perform locomotion tasks and manipulation tasks that either a single robot cannot perform, or would require a special-purpose larger robot to perform. They can also coordinate to perform search and reconnaissance tasks exploiting the efficiency that is inherent in parallelism. They can also perform independent tasks that need to be coordinated. Networked robots also result in improved efficiency. Tasks like searching or mapping, in principle, are performed faster with an increase in the number of robots. A speed-up in special military operations can be achieved by deploying multiple robots performing operations in parallel, but in a coordinated manner. Perhaps the biggest advantage to using the network to connect robots is the ability to connect and harness physically-removed assets. Mobile robots can react to information sensed by other mobile robots in the neighbor areas. Human users can use machines that are remotely located via the network. The ability to network robots also enables fault-tolerance in design. If robots can in fact dynamically reconfigure themselves using the network, they are more tolerant to robot failures. Finally, networked robots have the potential to provide great synergy by bringing together components with complementary benefits and making the whole larger than the sum of the parts.

Implementation Aspects

Robitized systems dedicated for military purposes are refered to as military robots. They can be designed in different forms and can be intended for different purposes such as: remote controlled weapon stations, unmanned mobile ground stations (wheel-based or track-based mobile

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robots), unmanned aerial vehicles (robotized aircraft) and unmanned marine systems. All of them can have a certain level of autonomy and intelligence. The scope of this paper is oriented towards consideration of ground mobile robotic systems and their potential applications in military tasks. These robots can be categorized according to their use in the following way: (i) mobile robotic systems for remote surveillance and monitoring, (ii) combat mobile robots, and (iii) mobile robots for special purposes. The difference among them relates to complementary sensorial and equipment (weapon) systems while the similarity concerns mainly the use of a mobile wheel- or track-based platfrom (Fig.1) designed to enable an increased mobility and manouverability of a particular robotic device. The examples of several contemporary advanced mobile robotic platforms (e.g Andros (US) and PACKBOT 510 EOD (France)) with corresponding specially designed robotic arms are shown in Fig.1.

a b c

Figure 1. Different models of contemporary hi-tech mobile robots: a) Andros MARK VA-1, b) Andros WOLVERINE [2], and c) PACKBOT 510 EOD (Explosive Ordnance Disposal) [3]

The examples of advanced automatic terrain military systems developed in the Military Technical Institute - VTI (Serbia) are presented in Fig. 2a, 2b and 2c.

Figure 2a. Automated anti-tank system – APOS [4]-[7]

Figure 2b. Modular robotic system – MILICA [4]-[7]

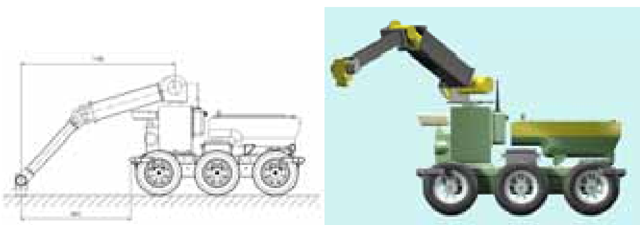

Figure 2c. CAD model of an unmanned middle-sized wheeled ground vehicle with an embedded robotic arm designed for special purpose

The principle of operation of different autonomous mobile robotic systems and unmanned vehicles developed for different advanced applications is based on the existence of two functional modules: (i) mobile base station and (ii) remotely-controlled system (e.g. robot) as presented in Fig.3.

Bearing in mind the enormous importance of building and application of such mobile robotic systems, accurate modeling, navigation, control and appropriate experimental testing and verification are unavoidable steps in the design and development of these dynamic systems.

Figure 3. Concept of a remotely supervised mobile robotic system – mobile robot (left) and base-station (right) with a corresponding command and wireless communication interface

Modeling of Mobile Robotic Systems

A kinematic model of a mobile robotic platform with a robotic arm attached can be defined by a kinematical scheme presented in Fig.4. Regardless of the type of traction (wheel- or track-based), a mobile platform has 6 dof in a general case while the robot arm commonly has 6 or 7 dof depending on task requirements and requests for anthropomorhic, dexterous objects handling. In this paper we consider a robotic system with 12 dof in total, i.e. 6 dof for the mobile platform (3 translational x, y, z and 3 rotational joints Ψ, θ, ϕ,) and 6 dof for the robotic arm q_1... q_6.

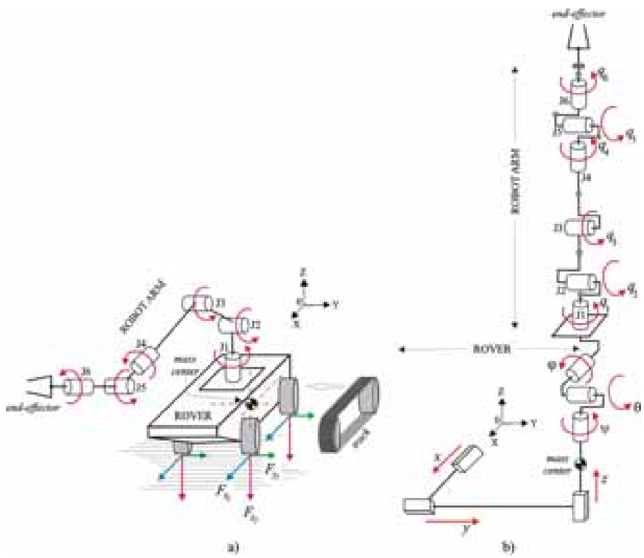

Figure 4. a) 3D model of a wheeled/tracked mobile robot with the robotic arm and the end-effector attached to the tip of the arm, b) Kinematic scheme of a mobile robotic system with particular joints

The presented model of the robotic system (Fig.4) consists of two functional modules: (i) the mobile robotic platform and (ii) the robotic arm. Contemporary mobile robotic platforms are driven by wheels or tracks depending on their implementation purposes (indoor or outdoor) and the ground surface structure. As far as modelling complexity is concerned, there are no significant differences if the robot is driven by wheels or trucks. In both cases the models are nonlinear and include modelling of traction/braking forces in the longitudinal, lateral and vertical directions. Without losing generality, a four-wheel driving (4WD) mobile platform is considered in the paper. Similar relations can be derived for corresponding 6WD or track-based ground vehicles.

A 4WD mobile robot platform with differential steering is considered in the paper as a system representative. A 3D model of a mobile robot is considered taking into account that robot can move on the sloped surface. In the general case, a surface inclination angle can appear in both longitudinal γ_x as well as lateral γ_y direction of motion. The forward (transport) speed $\vec{V}$ (Fig.5) direction depends on the tyre angular velocities, the robot parameters as well as the ground surface parameters and conditions. Robot motion is considered in the inertial $OXYZ$ coordinate system attached to the ground surface. The local coordinate system $oxyz$ is attached to the center of mass of the mobile robotic platform and it is mobile, too. The motion of the robot platform is a consequence of the independence differential driving (rotation) of robot wheels. The corresponding longitudinal $F_{xi}, i=1,4$ and lateral $F_{yi}, i=1,4$ tyre forces produce desired robot motion and desired forward speed. The forward speed $\vec{V}$ in the general case is not colinear with the direction of the robot longitudinal axis of symetry. The angle between the velocity vector $\vec{V}$ and the longitudinal axis of symetry x is defined by the angle β known as a slip angle [8]. Particular wheels perform corresponding rotational as well tranlsational movements. The tyre linear, i.e. translational velocities presented in Fig.4 are signed as $\vec{v}_i, i=1,4$. These tyre linear velocities do not coincide with the corresponding direction of motion in the general case. The conseqence is appearance of the tyre slip angles $\varsigma_i, i=1,4$ as presented in Fig.5. Some important geometry parameters of the rover are presented in Fig.5: b - track of the rover, l_r - rear wheels axis distance from the center of mass, l_f - front wheels axis distance from the center of mass, and h_C - height of the center of mass with respect to the ground surface. The vector of state variables that define the robot position in the inertial coordinate system $OXYZ$ is in the general case of 6×1 order. The planar vehicle dynamics (vehicle dynamics in the plane of motion) is considered in the paper although the terrain surface inclination will be taken into account. Assuming the previous simplification, the robot state variables including three coordinates can be defined in the vector form:

$$q = \left[X\ Y\ \varepsilon\right]^T \qquad \dot{q} = \left[\dot{X}\ \dot{Y}\ \dot{\varepsilon}\right]^T \tag{1}$$

where X and Y are the translatory displacements in the corresponding coordinate directions and ε is the yaw angle about the vertical axis which passes through the center of mass. The dynamic model of the 4WD rover presented in Fig.5, defined by the corresponding geometry parameters, kinematic variables and the vector of state variables (1), can be defined as:

$$T = H(q)\cdot\ddot{q} + h_{ccg}(q,\dot{q}) - F_w \tag{2}$$

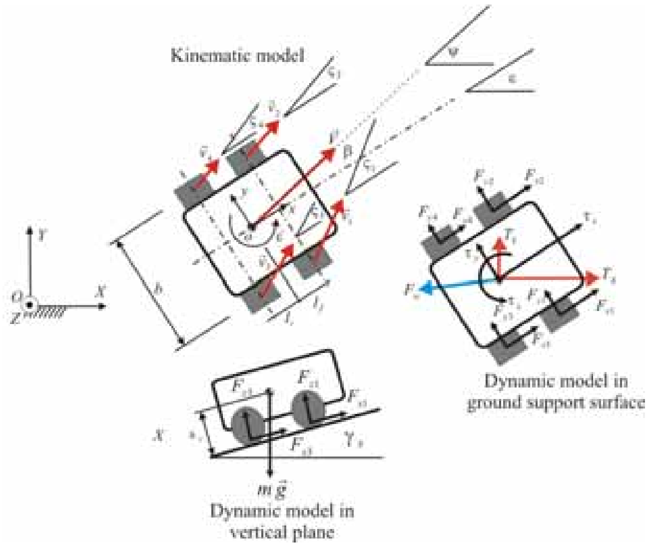

Figure 5. Kinematic and dynamic model of the 4WD mobile robot platform (rover) with the corresponding variables and kinematic parameters

where $T \in \Re^{3\times1}$ is the vector of generalized (traction/braking) forces and torques that act in the robot center of mass and has three components in the main coordinate directions (Fig.5): two generalized forces T_X and T_Y (T_Z is not considered in (2) bearing in mind that Z is not a state variable (1)) and the yaw torque T_ε ; $H \in \Re^{3\times3}$ is the inertia matrix of the rover; $h_{ccg} \in \Re^{3\times1}$ is the vector of centrifugal, Coriolis and gravity forces acting upon the system and $F_w \in \Re^{3\times1}$ is the vector of external resistance forces and torques including aerodynamic resistance, rolling resistance, Coulomb friction, etc. The vector of driving/traction forces and troques acting in the vehicle center of mass, expressed in the local coordinate system $oxyz$ (Fig.5) attached to the center of mass (MC) can be defined in the form:

$$\tau = \begin{bmatrix}\tau_x\\ \tau_y\\ \tau_\varepsilon\end{bmatrix} = \begin{bmatrix}\sum_{i=1}^{4} F_{xi}\\ \sum_{i=1}^{4} F_{yi}\\ M_Z\end{bmatrix} \tag{3}$$

$$M_Z = \left(F_{x1}+F_{x3}-F_{x2}-F_{x4}\right)\cdot\frac{b}{2} + \left(F_{y1}+F_{y2}\right)\cdot l_f - \left(F_{y3}+F_{y4}\right)\cdot l_r \tag{4}$$

The traction/braking forces at the vehicle tyres are calculated by the non-linear Pacejka tyre model known as a *"magic formula*" tyre model [8, 9]. The longitudinal and lateral commponents $F_{xi}, F_{yi}, i=1,4$ depend on two kinematic variables: the tyre slip ratio s_i and the tyre slip angle α_i . Both variables can be calculated according to [8, 9] from the following relations:

$$s_i = \frac{v_i \cos(\alpha_i) - r_i\,\omega_i}{r_i\,\omega_i} \tag{5}$$

$$\alpha_i = \delta_i - \varsigma_i \tag{6}$$

$$\begin{aligned} v_1 &= \sqrt{(\dot{y} + l_f \dot{\varepsilon})^2 + (\dot{x} - b/2\,\dot{\varepsilon})^2} \\ v_2 &= \sqrt{(\dot{y} + l_f \dot{\varepsilon})^2 + (\dot{x} + b/2\,\dot{\varepsilon})^2} \\ v_3 &= \sqrt{(\dot{y} - l_r \dot{\varepsilon})^2 + (\dot{x} - b/2\,\dot{\varepsilon})^2} \\ v_4 &= \sqrt{(\dot{y} - l_r \dot{\varepsilon})^2 + (\dot{x} + b/2\,\dot{\varepsilon})^2} \end{aligned} \tag{7}$$

$$\begin{aligned} tg(\varsigma_1) &= \frac{\dot{y} + l_f \dot{\varepsilon}}{\dot{x} - b/2\,\dot{\varepsilon}}, \quad tg(\varsigma_2) = \frac{\dot{y} + l_f \dot{\varepsilon}}{\dot{x} + b/2\,\dot{\varepsilon}} \\ tg(\varsigma_3) &= \frac{\dot{y} - l_r \dot{\varepsilon}}{\dot{x} - b/2\,\dot{\varepsilon}}, \quad tg(\varsigma_4) = \frac{\dot{y} - l_r \dot{\varepsilon}}{\dot{x} + b/2\,\dot{\varepsilon}} \end{aligned} \tag{8}$$

For every particular tyre $i = 1,4$, the angle δ_i represents a corresponding steering angle (in the case when the rover has such capability to change the orientation angles of tyres), v_i is the corresponding translatory speed of the centre of mass of the i-th particular tyre, and ς_i represents the tyre speed angle with respect to the longitudinal direction of motion of the robot platform *x*. The angles of tyre velocities are calculated from the following relations (8) according to [9].

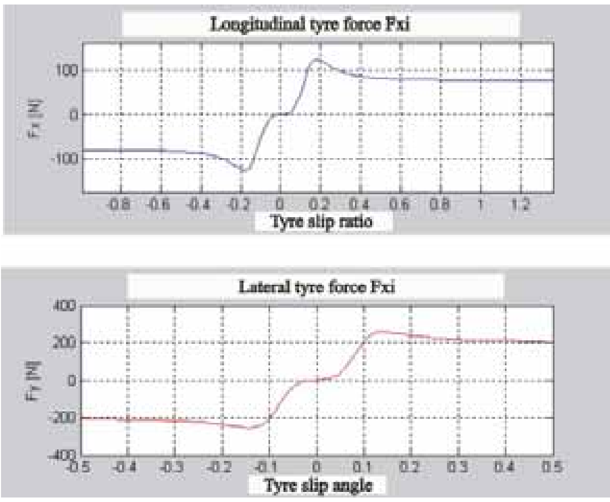

Figure 6. Non-linear tyre model characteristics – functional dependancy of longitudinal and lateral tyre forces from the kinematic variables: tyre slip ratio and tyre slip angle assuming that the tyre payload is constant or vary slightly during motion

Bearing in mind the non-linear character of the tyre model (Fig.6), the tyre forces are calculated from the relations given in their general form [8,9]:

$$F_{xi} = f_1(s_i, \alpha_i), \quad F_{yi} = f_2(s_i, \alpha_i) \tag{9}$$

The dependency between the generalized forces and the torques expressed in the absolute coordinate system and the local system attached to the MC of the rover (Fig.5) can be expressed in the following way:

$$\begin{aligned} T_X &= \tau_x \cos(\varepsilon) - \tau_y \sin(\varepsilon), \\ T_Y &= \tau_x \sin(\varepsilon) + \tau_y \cos(\varepsilon), \\ T_\varepsilon &= \tau_\varepsilon \end{aligned} \tag{10}$$

According to [8] and assuming that the mobile robot in this case is considered as a planar mechanism, the corresponding matrix and the vectors given in the model (2) can be assumed in the form:

$$H = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_Z \end{bmatrix} \tag{11}$$

$$h_{ccg} = \begin{bmatrix} -m\,\dot{y}\,\dot{\varepsilon} + m\,g\sin(\gamma_x) \\ m\,\dot{x}\,\dot{\varepsilon} + m\,g\sin(\gamma_y) \\ 0 \end{bmatrix} \tag{12}$$

$$F_w = F_a + F_{tr} \tag{13}$$

where *m* is the robot mass, *Iz* is the robot axial moment of inertia with respect to the axis *z*, *g* is the gravity acceleration. The resultant vector of the aerodynamic resistance as well as of the rolling resistance forces and the torques is determined according to [8] and has the form:

$$F_w = \begin{bmatrix} -K_x \dot{x}^2 - \sum_{i=1}^{4} f_{r_i} F_{z_i} \cos\zeta_i \\ -K_y \dot{y}^2 - \sum_{i=1}^{4} f_{r_i} F_{z_i} \sin\zeta_i \\ -K_\varepsilon \dot{\varepsilon} \end{bmatrix} \tag{14}$$

where K_x, K_y represents the corresponding air resistance coefficients obtained experimentally for the particular robot and K_ε is the yaw-rate damping coefficient depending on the tyre-ground conditions; f_{r_i} is the rolling resistance coefficient of the *i*-th tyre, and F_{z_i} represents the corresponding *i*-th tyre payload.

The model determined by relations (2)-(14) will be used for the synthesis of the dynamic control of the mobile robotic system motion. The corresponding model of the robotic arm (Fig.4b) with an end-effector will not be considered in the paper since it is well known from the broad literature (e.g. [10]).

Intelligent Navigation and Control

Crucial tasks to be solved with autonomous mobile robots are how to navigate and control such systems in operating in unknown and unstructured environment. There are a lot of contributions in this field of research. The most appropriate way to control autonomous motion of such systems is to combine conventional and intelligent control techniques including implementation of fuzzy inference systems (FIS) and learning algorithms. Soft computing algorithms can be used very efficiently to enable environment understanding, spatial reasoning, sensor-based intelligent navigation, path planning, obstacle avoidance, etc., while a dynamic control is commonly used for trajectory tracking and keeping desired dynamic performances of the system necessary for accurate task performance. In that sense, an appropriate control architecture is proposed in the paper and shown in Fig.7.

The role of a human operator is to impose a referent (desired) task (e.g. the parameters of terrain mission) as well as to supervise the overall system operation. The operator uses a corresponding command interface installed in the base-station (Fig.3) to supervise the system behaviour using remote wireless communication with the mobile robotic system. The robotic system has autonomous characteristics to an extent allowed by the operator. Depending on available sensorial equipment attached to it, the robot can be fully autonomous or semi-autonomous. The most usual task to be introduced by a human operator (e.g. commander) to the mobile robot represents a requirement to track different routes of motion and perform some manipulative or combat tasks. The operator and the robot use corresponding digital maps and the GPS system to impose and perform a desired motion. Environmental surveillance or remote navigation can be imposed in an easy way using a corresponding command interface by a simple definition of the control points (CP) using the GPS navigation and coordinates (longitude, latitude, altitude), as presented in Fig.8.

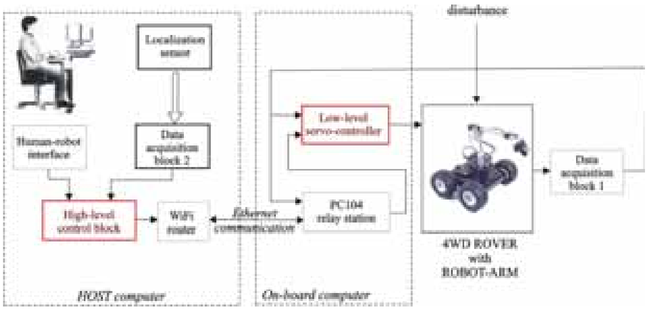

Figure 7. Block-scheme of the robot hierarchy control architecture with two control levels - high-level and low-level modules

The control system for the autonomous operation proposed in the paper represents a hierarchical structure that consists of two functional levels (Fig.7): (i) high-level, and (ii) low-level. The high control level serves for cognitive tasks such as navigation, path planning and colision avoidance. At the low-level, distribution of the control payload per particular tyres is provided. The payload has to be uniformly distributed per robot wheels. The wheels at the same side of robot usually have the same angular velocities of rotation in order to simplify differential control distribution bearing in mind that wheeled robots represent overactuated systems.

Figure 8. Example of a desired motion of a mobile robot imposed in real outdoor environment by the GPS coordinates of the array of check-points

When the autonomous mobile robot moves towards the target position and when the sensors detect an obstacle, an avoiding strategy is necessary to be employed. In that sense, the robot motion represents a compromise between avoiding obstacles and moving towards the target position (Fig.8). Intelligent robots response to both sensed variables – a relative distance and orientation of the obstacle(s) with respect to the robot as well as the relative position of the target with respect to the robot direction of motion (Fig.9). By moving towards the target location and avoiding obstacles, the mobile robot changes its orientation and forward velocity. When the obstacle is detected to be near, the mobile robot slows down and quickly changes its orientation as a consequence. The navigation strategy has to enable the robot to come as near to the target position as possible while avoiding collision with mobile and immobile obstacles in its neighborhood in the same time. The fuzzy-logic-based control can be efficiently applied for navigation of autonomous robotic systems in the presence of obstacles in unknown environment [11 - 17].

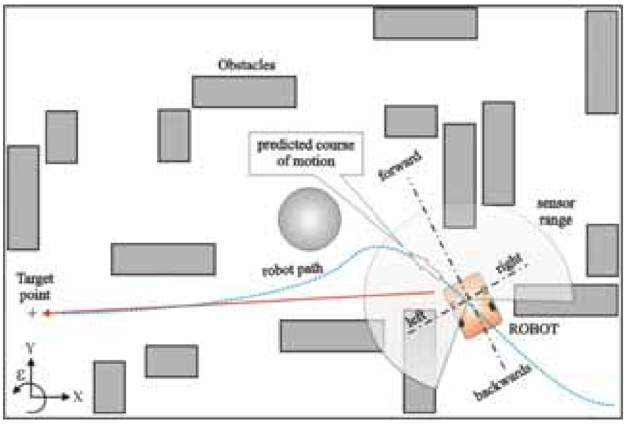

Figure 9. Model of obstacle avoidance and spatial reasoning used for building corresponding Fuzzy Inference Systems (FIS) to be implemented within the high-level control block (Fig.7)

The block-diagram of a fuzzy inference system to be employed for robot navigation in the presence of immobile obstacles is shown in Fig.10. Three functional modules exist within the proposed FIS: the fuzzification block, the inference block and the defuzzification module. The inference block uses fuzzy rules to realize intelligent navigation. The fuzzification and defuzzification blocks consist of several membership functions whose shapes are given in Figures 11 - 13. The appropriate fuzzy rules of the FIS are presented in Fig.14.

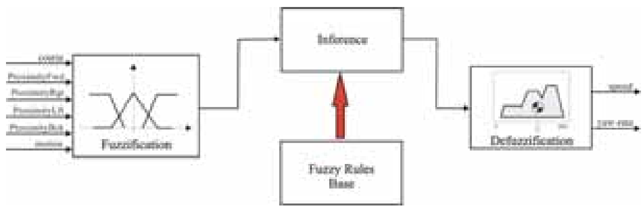

Figure 10. Block scheme of the FIS developed for obstacle avoidance with six input and two output variables

The intelligent mobile robot reactive behavior is determined by corresponding fuzzy rules. The inputs to the fuzzy controller shown in Fig.10 are: (i) the "*course*" of motion (Fig.9), i.e. the azimuth angle determined as a result of a compromise between the motion towards the target point and the nearest free corridor between the obstacles in the neighborhood, (ii) the "*proximityFwd*" which is the front side proximity to the closest obstacle, i.e. the distance between the front side of the robot and the closest obstacle (Fig.9), (iii) "*proximityRgt*" which is the right-hand side proximity to the nearest obstacle, (iv) "*proximityLft*" which is the left-hand side proximity to the nearest obstacle, (v) "*proximityBck*" which is the rear side proximity to the nearest obstacle, i.e. back distance to obstacles, and (vi) "motion" indicator regarding the modus of motion – forward, backward or standby. The outputs of the fuzzy controller are: (i) "*speed*" that represents commanded speed with respect to the longitudinal axis of the robot, and (ii) "*yawrate*" which is the commanded yaw rate of the mobile robot about the vertical axis of rotation.

The "*course*" angle is determined relatively to the local coordinate system attached to the robot MC and with the x-axis oriented along the longitudinal axis of the robot platform. The course is positive when the robot has to turn to the left and negative when it moves to the right. The block diagram of the fuzzy inference system is presented in Fig. 10. The corresponding membership functions that correspond to the particular input variables are given in Figures 11 - 13. The input variables "*proximityFwd*" and "*proximityBck*" have the same shape of the membership functions as well as the "*proximityRgt*" and the "*proximityLft*" (Fig.12).

The FIS rule database consists of 16 rules that provide the system to behave properly in the presence of immobile obstacles without collision. The rule data-base is shown in Fig.14.

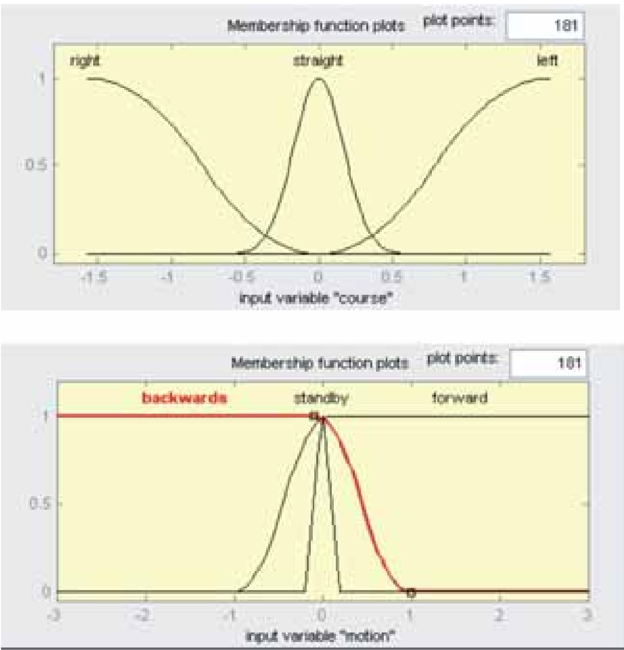

Figure 11. FIS input membership functions "course" and "motion"

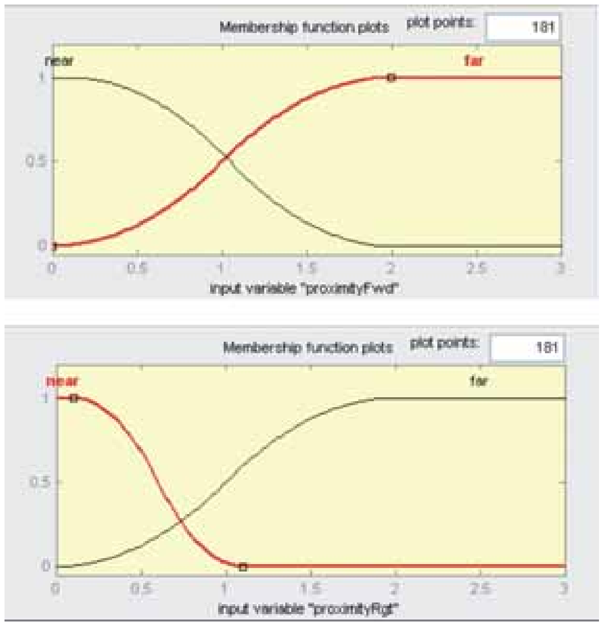

Figure 12. FIS input membership functions "proximityFwd" and "proximityRgt"

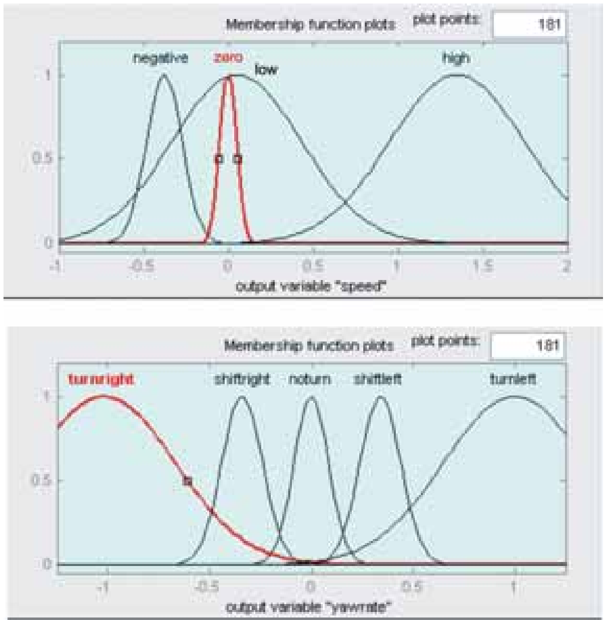

Figure 13. FIS output membership functions "speed" and "yawrate"

Fuzzy Inference System – Rule Data Base									
				Input variables			Output variables		Weighting factor
Rule No.	course (rad)	proximity Fwd (m)	proximity Bck (m)	proximity Rgt (m)	proximityLft (m)	Motion (m/s)	Speed (m/s)	Yaw/rate (rad/s)	
1	straight	far	none	none	none	forward	high	noturn	1
2	straight	near	none	none	none	forward	low	noturn	1
3	right	none	none	not near	none	forward	low	turnright	1
4	left	none	none	none	not near	forward	low	noturn	1
5	none	none	none	near	near	forward	low	noturn	1
6	none	none	none	near	not near	forward	not hight	shiftleft	1
7	none	none	none	not near	near	forward	not high	shiftright	1
8	none	none	not near	none	none	not forward	negative	none	1
9	none	near	near	not near	not near	none	low	shiftright	1
10	none	near	near	near	near	none	zero	shiftright	1

Figure 14. FIS rules for the obstacle avoidance task

Integrated Control Based on Model of Dynamics

According to the previous consideration and description of the robot model (2)-(14) and the FIS (Fig.10) to be designed for intelligent navigation in the presence of obstacles, it is possible to propose an appropriate control strategy that should enable fullfiling three basic tasks with mobile robots: (i) accurate navigation, (ii) trajectory tracking and (iii) satisfactory dynamic performances. Bearing in mind these facts, a corresponding dynamic control, based on the knowledge of the robot dynamics (model), is needed to satisfy control requirements. The human operator imposes a referent trajectory (position and orientation) of the robot motion q_0 as well as a referent speed (longitudinal, lateral and yaw-rate) of the motion $\dot{q}_0$ according to (1). The referent values of the robot forward (transport) speed V_0 and the corresponding yaw angle ε_0 are imposed by the command interface and can be modified automously by the FIS taking into account that the robot can meet obstacles during motion. The modified robot velocity V_0 and the commanded yaw-rate $\dot{\varepsilon}_0$ resulted from the FIS cognitive block (Fig.7) represent new referent values to be used as inputs in the dynamic control algorithm. The control algorithm that should provide accurate trajectory tracking and fine dynamic perfromances of the robotic system is based on the knowledge of the robot model (2). Then, the control algorithm can be written in the following form in a simmilar way as with unmanned ground vehicles [18]:

$$T = H(q)\cdot\hat{\ddot{q}} + h_{ccg} - F_w,$$
$$\hat{\ddot{q}} = \ddot{q}_0 - K_d\left(\dot{q}-\dot{q}_0\right) - K_p\left(q-q_0\right) \tag{15}$$

where K_p and K_d are corresponding proportional and differential control gains. The vectors q_0, $\dot{q}_0$ and $\ddot{q}_0$ are calculated on the basis of the referent values V_0 and ε_0 obtained from the higher control level, i.e. from the cognitive block. They provide the following variables regarding the speed of motion in three coordinate directions: longitudinal, lateral and yaw one:

$$\begin{aligned}\dot{x}_0 &= V_0\cos(\varepsilon_0)\\ \dot{y}_0 &= V_0\sin(\varepsilon_0)\\ \dot{\varepsilon}_0 &= \dot{\varepsilon}_0\end{aligned} \tag{16}$$

where ε_0 are determined from :

$$\varepsilon_0 = \int \dot{\varepsilon}_0 \cdot dt \tag{17}$$

Now, the nominal speed vector $\dot{q}_0$ can be expressed in the form:

$$\dot{q}_0 = \left[\dot{x}_0\ \dot{y}_0\ \dot{\varepsilon}_0\right]^T \tag{18}$$

And the corresponding nominal acceleration is obrained from the relation:

$$\ddot{q}_0 = \frac{d\,\dot{q}_0}{dt} \tag{19}$$

From (15) the control (traction/braking) forces T_X, T_Y and the control (yaw) torque T_ε can be calculated with respect to the absolute coordinate system (Fig.5). From (10) the driving forces and the torques in the longitudinal τ_x, lateral τ_y and yaw τ_ε direction are determined. These values can be calculated from the relations:

$$\begin{aligned}\tau_x &= T_X\cos(\varepsilon) + T_Y\sin(\varepsilon),\\ \tau_y &= -T_X\sin(\varepsilon) + T_Y\cos(\varepsilon),\\ \tau_\varepsilon &= T_\varepsilon\end{aligned} \tag{20}$$

The control forces/torques τ_x, τ_y and τ_ε are produced by corresponding tyre forces distributed in an appropriate way among the four wheels. The 4WD mobile robotic platform is "overactuated" since generally there are four driving wheels and motion is performed in three coordinate directions: x, y and ε. Theoretically, there are eight tyre force commponents $F_{xi},\ i=1,4$ and $F_{yi},\ i=1,4$ that should enable a desired motion of the robot body. Practically, that requires the unknown forces $F_{xi},\ i=1,4$ and $F_{yi},\ i=1,4$ should be determined from the relations (3) and (4) taking into account the pre-determined generalized forces/torques τ_x, τ_y and τ_ε. In order to mathematically determine the calculation, certian assumptions must be assumed so as to simplify the calculation of unknown control variables. The following simplifications can be assumed without losing the system maneouverability and fine dynamic performances:

$$\begin{aligned}&F_{x3}\equiv F_{x1},\ F_{x4}\equiv F_{x2},\\ &F_{y2}=\kappa_2\cdot F_{y1},\ F_{y3}=\kappa_3\cdot F_{y1},\ F_{y4}=\kappa_4\cdot F_{y1}\end{aligned} \tag{21}$$

where $\kappa_i = F_{yi}/F_{y1},\ i=1,3$ are the corresponding coeficients regarding the lateral force amplitudes with respect to the referent value characteristic for the tyre signed as no. 1. Taking into account the assumptions (21) and including them in (3) and (4), then three equations with corresponding three unknown variables F_{x1}, F_{x2} and F_{y1} can be determined:

$$\begin{aligned}\tau_x &= 2\cdot F_{x1} + 2\cdot F_{x2},\\ \tau_y &= \left(1+\kappa_2+\kappa_3+\kappa_4\right)\cdot F_{y1},\\ \tau_\varepsilon &= b\cdot F_{x1} - b\cdot F_{x2} + \left[\left(1+\kappa_2\right)\cdot l_f - \left(\kappa_3+\kappa_4\right)\cdot l_r\right]\cdot F_{y1}\end{aligned} \tag{22}$$

From the system of equations (22) the unknown forces can be calculated to satisfy control requirements. The calculated tyre forces represent the control variables but the true control variables are particular angular velocities of the robot wheels $\omega_i,\ i=1,4$. Since, according to the simplifications (21) the rotations of the right-hand side and left-hand side wheels are controled in pair, the wheel angular velocities ω_i are calculated from the kinematical relation (5) which defines the tyre slip ratio. Since the longitudinal $F_{xi},\ i=1,4$ and the lateral tyre forces $F_{yi},\ i=1,4$ are non-linear functions (relations (9) and Fig.6) of the tyre slip ratios s_i and the tyre slip angles α_i that implies the unknown variables are calculated by solving an inverse mathematical problem of the model given by relations (9). In the last step of the control signal determination, the tyre angular velocities ω_i are calculated from (5) as the first-hand control variables. It is enough to determine the corresponding angular velocities for single, right and left particular wheels since the wheels on the same side rotate with the equal speeds of roation.

Experimental Verification

For the purpose of control verification an experimental test-bed system was developed [19]. The control strategy proposed in Section 4, whose architecture is presented in Fig.7, was implemented to control a small 4WD rover (wheel-based mobile robot [20]), Fig.15. A complementary Matlab/Simulink modelling and simulation software toolbox *Virtual WRSN* (Wireless Robot and Sensor Networks) was developed and used for building high-level control algorithms concerning cognitive robot behaviour in unknown environment and in the presence of obstacles. The experimental verification of control efficiency in the laboratory conditions was performed using a fully equipped mobile robotic platform with obstacle detection sensors (laser scanner range finder, ultrasonic sensors, stereo vision, gyroscopes, accelerometers, etc.). The test-bed scenario presented in Fig.15 is re-configurable assuming a possibility to change the position of obstacles. Different real situations of robot operation in indoor conditions can be thus tested in real-time. The control architecture proposed in this paper is scalable. It can be implemented with different real large-scale dynamic systems such as mobile robotic platforms designed for military missions as for example presented in Fig.2b. The models and control principles given in Sections 3 and 4 can be easily adapted to real applications with wheel-based as well as with track-based mobile robots.

Figure 15. Experimental test-bed station [19] built for research and development of control and navigation of autonomous mobile robotic systems

Conclusion

The paper regards theoretical and some practical aspects of building control architecture for autonomous mobile wheel-based robots. The control strategy is based on a combination of intelligent control algorithms (fuzzy logic reasoning, navigation and path planning) within a high-level cognitive block and dynamic control based on a robot model at the low level to ensure accurate trajectory tracking and fine dynamic performances during operation. An experimental, scalable model of a test scenario in indoor conditions was developed for research and verification of the proposed control strategy. Advanced military or civil robot applications with autonomous robots in real conditions can be derived from the experimental model developed and described in the paper, applying the proposed control methodology and an appropriate sensorial system.

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Senzorski zasnovana inteligentna navigacija i upravljanje autonomnim mobilnim robotima namenjenim za obavljanje složenih terenskih zadataka

U radu se razmatra inteligentna, na senzorskim informacijama zasnovana, navigacija i upravljanje u nepoznatoj okolini i prisustvu prepreka. Rad se bavi razmatranjem kombinovanog fuzzy i dinamičkog upravljanja autonomnih mobilnih robota i njihovog kretanja u nepoznatoj sredini s preprekama različitih oblika i distribucije. Strategija upravljanja i algoritmi opisani u radu su pogodni za primenu kod bežičnog daljinskog upravljanja kretanjem mobilnih robota u različitim izvršnim scenarijima i zemaljskim misijama od interesa za napredne vojne i civilne primene. Daje se detaljan matematički model pokretne robotske platforme i odgovarajuća hijerarhijska upravljačka struktura na dva nivoa, s kognitivnim blokom na višem nivou namenjenom inteligentnoj navigaciji i planiranju kretanja u prostoru i odgovarajućim dinamičkim upravljanjem i kontrolerom praćenja putanje na nižem hijerarhijskom nivou. Detaljan opis strukture predloženog fuzzy sistema odlučivanja je predstavljen u radu. Neki aspekti primene kao i eksperimentalna verifikacija predloženog upravljanja se takođe opisuje u radu.

Ključne reči: **roboti, robotizovano vozilo, izbegavanje prepreka, upravljanje kretanjem, daljinsko upravljanje, navigacija, veštačka inteligencija, sistem zaključivanja, matematički model.**

Сенсорная интеллектуальная навигация и управление автономными движущимися интеллектуальными роботами, назначеными для развитых миссий на Земле

B hasto}|ей rabote рассматривается интеллектуальная навигация, обоснованая на сенсорных информациях и управление в незнакомой окружающей среде и при наличии препятствий. Работа охватывает рассматривание комбинированного fuzzy и динамического управления автономных движущихся интеллектуальных роботов и их движения в незнакомой окружающей среде с препятствиями различных форм и распределений. Стратегия управления и алгорифмы описаны в работе удобны для применения у беспроволочного сенсорного телеуправления движением движущихся роботов в различных исполнительных событиях и в развитых мисиях на Земле от особого интереса для развитых военных и гражданских применений. Здесь показана подробная математическая модель движущейся робототехнической платформы и соответствующая иерархическая управляющая структура на двух уровнях с осознательным блоком на высшем уровне, назначеном для интеллектуальной навигации и планирования движения в пространстве и соответствующим динамическим управлением и контролерем сопровождения орбиты на нижнем иерархическом уровне. В работе представлено и подробное описание структуры предлагаемой fuzzy системы решения. Тоже в работе описаны и некоторые точки зрения применения, а в том числе и экспериментальное удостоверение подлинности предлагаемого управления.

Kly~evwe slova: **Интеллектуальный робот, робототехническая машина, избегать препятствие, управление движением, сенсорное телеуправление, навигация, искусственный интеллект, sistema логического вывода (умозаключения), математическая модель.**

Contrôle et navigation intelligents via capteurs pour robots mobiles autonomes en missions avancées sur terrain

Ce travail concerne le contrôle de la navigation d'un robot mobile intelligent équipé de capteurs dans des environnements inconnus et en présence d'obstacles.Il s'agit de combiner le contrôle flou de la dynamique des robots autonomes et leur mouvement. La stratégie proposée pour le contrôle ainsi que les algorithmes décrits dans ce travail sont adaptés pour le contrôle à distance sans fil du mouvement des robots mobiles dans le cadre de différents scénarii sur des terrains d'application réelles. Le modèle mathématique détaillé de la plateforme de robots mobiles est présenté ainsi que la structure du contrôle hiérarchique à double niveau. Il s'agit d'un bloc cognitif de haut niveau et d'un bloc de contrôle de bas niveau dédié au contrôle dynamique et au suivi des trajectoires. La description détaillée de la structure du système d'inférence flou est également présentée. Quelques implémentations et vérifications expérimentales du contrôle sont également décrit dans ce papier.

Mots clés: **robots, robot mobile autonome, évitement d'obstacles, contrôle dynamique, navigation, intelligence artificielle, système de conclusion, modèle mathématique.**