BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES
Vol. 52, No. 2, 2004

Inspection robot SAFARI – construction and control

P. DUTKIEWICZ, K. KOZŁOWSKI* and W. WRÓBLEWSKI

Institute of Control and Systems Engineering, Poznań University of Technology, 3a Piotrowo St., 60-965 Poznań, Poland

Abstract. The paper presents construction and control system of the climbing robot SAFARI designed at the Poznań University of Technology for inspection of high building walls, executed in order to evaluate their technical condition. Because such tasks are uncomfortable and very dangerous for humans, this mobile machine gives a possibility to observe and examine the state of the surface on which it is moving. The robot is a construction developed for walking on flat but uneven vertical and horizontal surfaces. Its on-board equipment provides ability to remotely examine and record images reflecting the robot's surroundings. At the beginning of the paper, several concepts of existing climbing robots (four-legged, six-legged, sliding platform) are outlined. Next, the mechanical system of the SAFARI robot is presented with special emphasis on its kinematic equations and description of movement stages. Then, the on-board manipulator as well as the sensor and control systems are described.

Keywords: walking robots, climbing robots, robot control, kinematics, sensor system.

1. Introduction

Mobile robots are especially destined for using in environments unfriendly and harmful for human beings. Other fields of possible mobile robot applications are tiresome, continuously repeated tasks or jobs requiring large physical power. In some tasks robots should move in a manner resembling humans or animals — they are then called walking robots.

The above application fields make mobile robotics (and particularly walking robots) one of the most rapidly developing areas in automation and robotics [1–3].

One of human-unfriendly tasks is inspection of high building walls, carried out to evaluate their technical condition. Because performing it on high elevations is very uncomfortable and dangerous for a human being, an idea has arisen to develop a climbing robot, giving a possibility to observe and examine the state of the surface on which the platform is moving. It causes that this robot — the mobile platform — should be autonomous with good mobility properties. The best solution seems to use a climbing robot. Since building walls are usually made of concrete with porous or cracked surfaces, inspection robot should be a walking machine, adapted for moving on vertical, irregular planes.

The inspection robot SAFARI [4] has been designed and developed at the Poznań University of Technology specifically for walking on flat but uneven vertical surfaces. It is equipped with vacuum feet, as only this solution is suitable for concrete surfaces. Its on-board equipment facilitates remote observation and recording of images reflecting the robot's surroundings. The whole system is composed of two separate parts: the mobile platform with all the necessary equipment on-board, and the stationary part — the system operator's console — which allows acquisition of data coming from a vision system, mounted on the mobile part.

The organization of the paper is as follows. Section 2 contains general remarks concerning climbing robots, presents typical four-legged, six-legged and sliding platform constructions of climbing robots. Section 3 concerns the mechanical construction of the robot, presents its kinematic equations and stages of movement. In the next section, technical information and the kinematic model of the on-board STRUS manipulator are outlined. Section 5 presents the structure of the sensor system. The last section describes the control system of the robot.

2. Properties of climbing robots

Climbing robots represent a specific kind of walking robots, which are useful while operating in environments unfriendly or harmful for a human. Moreover, climbing robots are specially designed for moving on sloping or vertical surfaces, as well as on horizontal ones (e.g. ceilings). In such situations, the influence of gravitational forces becomes very important — the design of the legs should assure reliable fastening to the working surface.

There are generally two ways of fastening the climbing robot to the surface:
- durable mechanical connection between the robot's grippers (legs) and the environment, using plier-like grippers; this is typical for robots climbing on constructions made of metal profiles (pipes, T-profiles, etc.);
- making use of adhesive forces between the gripper's surface and the working surface; the tightening force is produced by underpressure or — for robots climbing on surfaces made of ferromagnetic materials — electromagnetic grippers.

There exist many constructions [5,6] of climbing robots working not only in research laboratories, but also as important elements of industrial applications. The examples shown below illustrate a great variety of robot designs and the ways of adapting them to the expected tasks. In

* e-mail: krzysztof.kozlowski@put.poznan.pl

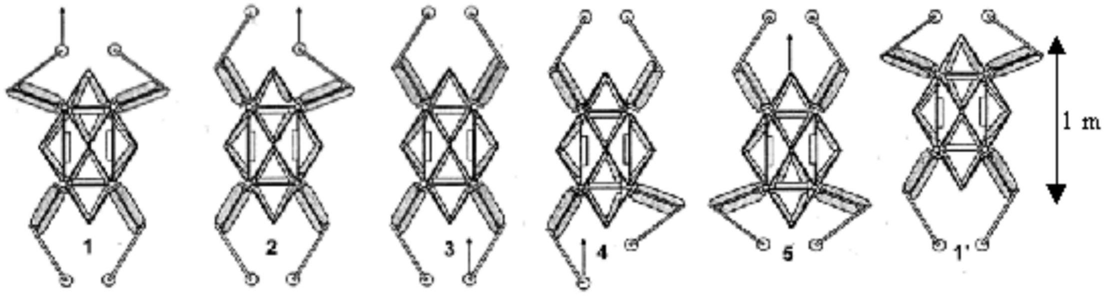

Fig. 1. Stages of movement of the four-leg Klettermax robot

its movement, a climbing robot should behave similarly to a human climber, i.e. at each time instant it should have a support at three points on the working surface. For example, a four-leg robot can move with only one leg at any given moment. This can be seen in Fig. 1 presenting the stages of movement of the four-leg robot Klettermax [5,6]. Its movement results from a sequence of movements of particular legs. Each limb has two joints; the pelvic and the knee. The Klettermax robot is very light when pneumatic actuators are employed.

The Ninja I [7,8] robots have been designed at the Tokyo Institute of Technology for such tasks as climbing buildings, bridges, and other constructions. Figure 2 presents the Ninja I robot and its movement abilities. The robot's weight is 45kG, it is 1.8m long, 0.5m wide and can move on a wall with a maximum speed of 7.4m/min. Each leg of the robot is driven with three prismatic actuators, working in parallel (so-called coupled drive). Prismatic joints are oriented vertically, in parallel to the direction of movement. As a consequence, the mass of the leg can be minimized and the total mass of the robot is distributed evenly (roughly) between all the legs. The feet of the robot are always oriented parallel to the ground as a result of an extra passive degree of freedom. Special contact/approach sensors placed around a foot allow the Ninja robot to change smoothly from climbing to walking. The Ninja I robots are equipped with special grippers — pneumatic VM-type (valve-regulated multiple) suction cups. Their surface is divided in many small cells — suction cups, which are controlled independently. This reduces underpressure losses in movement on rough (porous or cracked) ground.

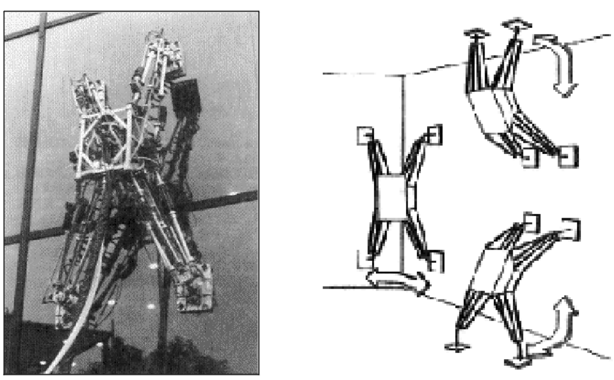

Fig. 2. The Ninja I robot and its movement abilities

The Rest robot [9] shown in Fig. 3 is an example of a six-legged robot. It is a reptile-like device and is destined for moving on ferromagnetic surfaces. During movement, each leg moves forward independently, as shown in Fig. 4. When all legs reach their final position, the body is moved forward — this kind of movement needs relatively large amounts of energy.

Very common in walking robot applications are sliding frame constructions. Their characteristic feature is the way of movement — the main elements of the construction slide relative to another one. They need special control strategies, but such constructions are especially well suited for climbing applications.

An example is the Wally robot [11], presented in Fig. 5. It uses two single pneumatic actuators, mounted in parallel. Suction cups are mounted at both ends of each actuator. Robot movement is ensured by synchronous control of actuator movement and of suction cups. It is necessary to control continuously the position of each actuator, which is difficult due to inherent nonlinearities.

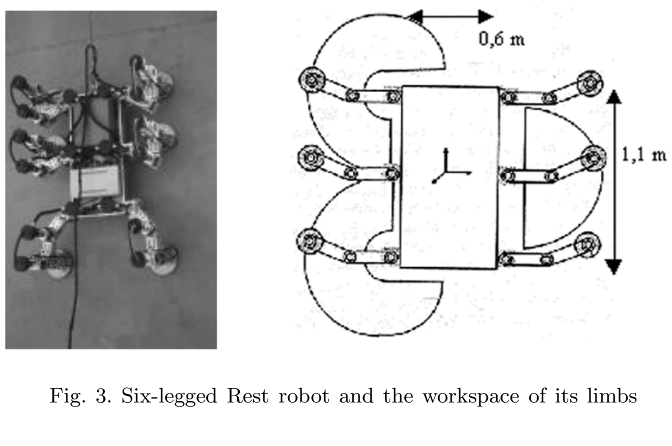

Fig. 3. Six-legged Rest robot and the workspace of its limbs

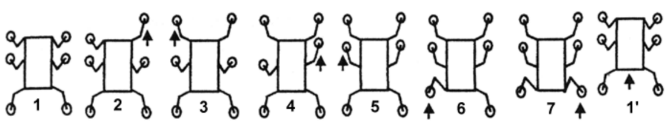

Fig. 4. Sequence of steps of the Rest robot

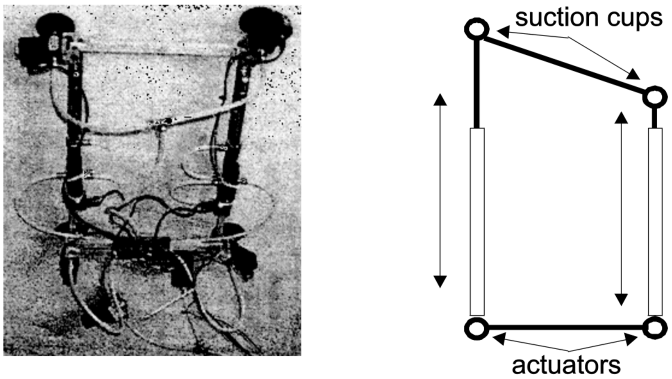

Fig. 5. Wally robot and its kinematic structure

It is also necessary to take into account friction effects, especially in the case of slow movement.

3. Mechanical structure

The design and construction of the Safari climbing robot has been supported by the Polish State Committee for Scientific Research under grant no. 8 T11A 010 17 'An inspection climbing robot for high-wall buildings'. The idea of such construction comes from the fact that inspection and maintenance work on high-wall buildings are dangerous and expensive tasks. In Poland many of such buildings are over twenty years old and the problem of their inspection is very important. So far, there have not been any constructions of climbing robots for inspection purposes available in Poland. The main function of the Safari robot is inspection of concrete structures such as walls of high-wall buildings. Equipped with suitable tools, the robot is also able to accomplish a great variety of maintenance tasks.

The Safari mobile platform represents a group of climbing robots with so-called sliding frame drive. It means that the platform (i.e. the body of the robot) moves in a plane parallel to the surface the robot operates on. Such mechanical construction facilitates implementing a modular structure, consisting of blocks of precisely defined functions. A general view of the Safari climbing robot is shown in Fig. 6. The robot consists of the following main modules:

- assembly module — a subsystem linking leg modules with the robot body,
- sliding platform module — allowing positioning of leg modules, carrying and moving measurement/actuating devices as well as communication with the operator,
- leg module, which is a link between adhesive modules and the assembly module; there are four leg modules,
- adhesive modules are responsible for adherence to the working surface.

Besides that, the robot is equipped with a supply unit and measurement/control devices assigned for performing particular tasks.

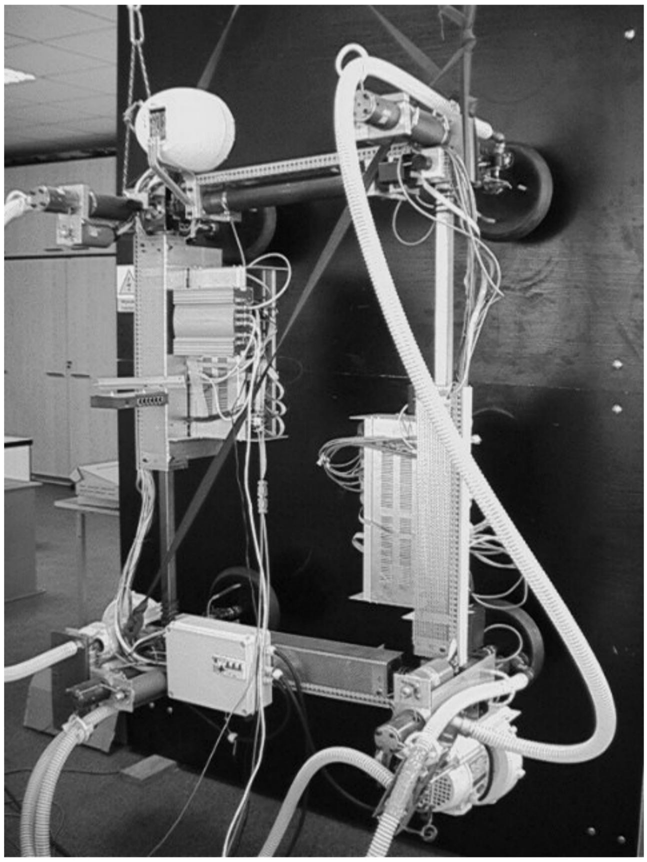

Fig. 6. General view of the Safari climbing robot

The mechanical structure of the Safari mobile platform supported by four legs is presented in Fig. 7. The top view of the mobile platform is shown on the left; the side view with one leg magnified is shown on the right. The sliding frame (the carrying structure) is of quadrilateral shape [4,11]. At the rest position, the sliding frame forms a square (600 mm × 600 mm, not including the sizes of extra devices — vacuum pumps, leg modules, etc.) with joints placed at its vertices. Four identical cylinders form the sides of the square. During movement the cylinders change their lengths. The sleeves of the cylinders are made of steel pipes of 60 mm diameter. Similarly, pistons moving inside cylinders are also made of steel pipes. A pulling screw is placed inside each piston; its rotation is transformed to translation and the cylinder length changes.

Each of the cylinders making up the body of the robot has its independent drive for leg positioning with a Maxon 80W DC motor. The mechanical moment is transmitted from the motor via a cog-belt gear to a shaft, on which the pulling screw is mounted. Linear drives of the sliding frame are connected with each other with four R-type passive degrees of freedom. Tho rotation axes of these passive degrees of freedom are perpendicular to the plane on which the robot moves. Such solution assures correct cooperation of drives without any program updates due to nonholonomic constraints. This kinematic structure

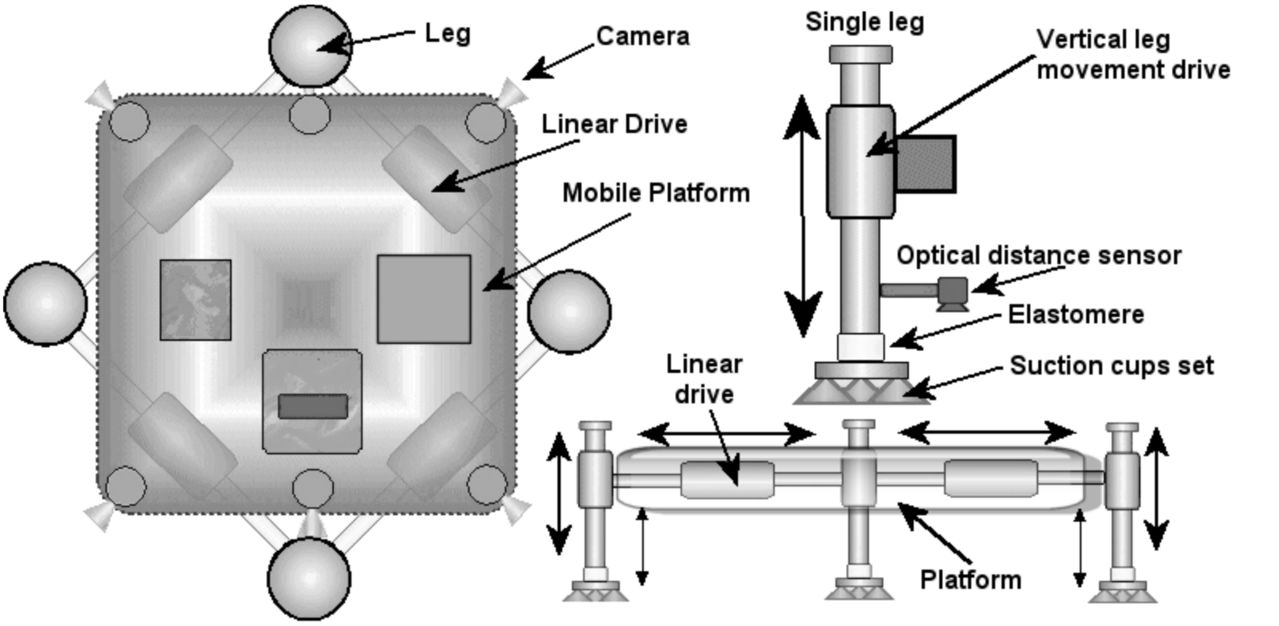

Fig. 7. Mechanical structure of the SAFARI climbing robot

requires adhesive fastening of three feet to the movement plane. In other words, at any moment only one suction cup may be lifted. This driving system enables horizontal moving of the leg, when it is lifted over the working plane.

Each leg is connected to two adjacent legs by linear drives, so that it can be positioned by changing the lengths of those two linear drives. During leg repositioning, only one leg is lifted up and down, while the other three legs must provide sufficient adhering force, holding the construction on the vertical movement plane. To put the leg in a new position, it is necessary to perform the following steps [11]:

1. release the fixing force by unsealing the suction cups or cutting out an airflow,
2. move the leg up by the vertical movement drive,
3. transfer the leg to a new position, using the two linear drives attached to the leg,
4. move the leg down by the vertical movement drive, and tighten it to the surface on which the robot moves,
5. try to seal the suction cups on the new position by applying underpressure to them,
6. if it is not possible to obtain significant adhering force in the new location, try to place the leg in another position (return to 1),
7. if it is possible to develop significant fixing force in the new location, calculate whether the force is sufficient to unseal and lift up the next leg, which is to be repositioned,
8. if repositioning is successful (the suction cups develop sufficient adhering force for lifting up the next leg), begin repositioning the next leg, according to the planned path and motion scheme.

Movement of the robot results from sequential displacements of the legs, one at a time [5,12]. Let A, B, C, D denote the starting positions of particular legs of the platform and A', B', C', D' — final, respectively (see Fig. 8). There are two kinematic problems — direct and inverse — which should be solved to derive the kinematic model of a mechanism. The solution of the direct kinematic problem means finding the position/orientation of the robot given by its joint coordinates, i.e. the current positions of its joints, drives, etc. On the other hand, the inverse kinematic problem requires calculating the joint coordinates necessary for the robot to reach the desired position/orientation.

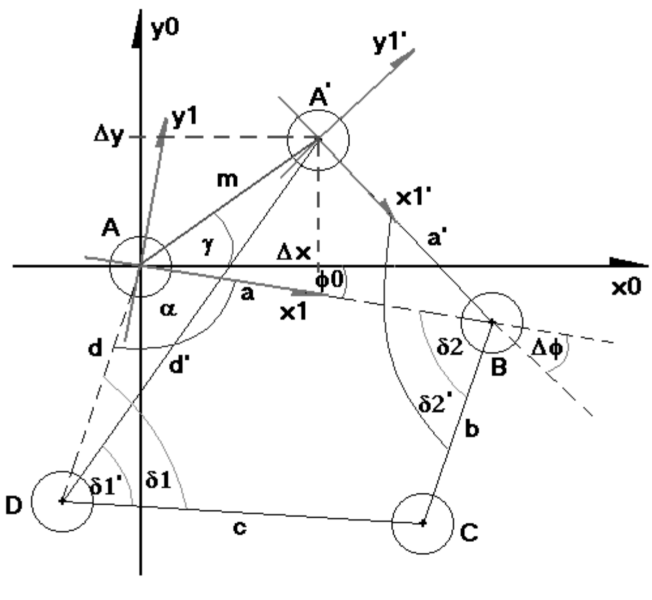

Fig. 8. Kinematic description of the displacement of the first leg

1. The displacement of the first leg from A to A' is shown in Fig. 8. It is assumed that $\varphi_0 < 0$. The inverse kinematic equations have the following form [12]:

$$m = \sqrt{\Delta x^2 + \Delta y^2}, \tag{1}$$

$$\gamma = \operatorname{atan2}(\Delta y, \Delta x), \tag{2}$$

$$a' = \sqrt{m^2 + a^2 - 2ma\cos(\gamma - \varphi_0)}, \tag{3}$$

$$d' = \sqrt{d^2 + m^2 - 2md\cos(\gamma - \varphi_0 + \alpha)}, \tag{4}$$

where m is the length of the leg displacement from A to A', Δx and Δy are the coordinates of m measured in the x_0y_0 coordinate frame, γ is the angle between the segment AA' and the x_0 axis (calculated with a 2-argument version of the 'arctan' trigonometric function). Moreover, a, d, a' and d' are the lengths of sections AB, AD, A'B and A'D, respectively. Based on Fig. 8, the formulae (1)–(4) can be easily processed to obtain the direct kinematic equations, which are as follows:

$$m = \sqrt{a'^2 + a^2 - 2a'a\cos(\delta_2' - \delta_2)}, \tag{5}$$

$$\sin(\gamma - \varphi_0) = \frac{a'\sin(\delta_2' - \delta_2)}{m}, \tag{6}$$

$$\cos(\gamma - \varphi_0) = \frac{m^2 + a^2 - a'^2}{2ma}, \tag{7}$$

$$\gamma = \operatorname{atan2}(\sin(\gamma - \varphi_0), \cos(\gamma - \varphi_0)) + \varphi_0, \tag{8}$$

$$\Delta x = m\cos\gamma, \tag{9}$$

$$\Delta y = m\sin\gamma, \tag{10}$$

$$\Delta\varphi = -(\delta_2' - \delta_2). \tag{11}$$

It is worth noting that any displacement of the first leg changes the robot orientation and the offset of the local coordinate system. Hence, when calculating the kinematics for the second leg, it is necessary to take into account the updated value of the desired change of orientation.

2. The displacement of the second leg from B to B' is shown in Fig. 9. Solving the inverse kinematic problem leads to calculating new desired lengths of arms a and b ensuring repositioning to the new position, while simultaneously minimizing the length of the arm b when the planned displacement is completed. The inverse kinematic equations, with known $\Delta\varphi$, have the following form:

$$d_1 = \sqrt{a^2 + b^2 - 2ab\cos\delta_2}, \tag{12}$$

$$\sin\psi = \frac{b\sin\delta_2}{d_1}, \tag{13}$$

$$\cos\psi = \frac{a^2 + d_1^2 - b^2}{2ad_1}, \tag{14}$$

$$\psi = \operatorname{atan2}(\sin\psi, \cos\psi), \tag{15}$$

$$b' = \sqrt{a'^2 + d_1^2 - 2a'd_1\cos(\psi + \Delta\varphi)}. \tag{16}$$

All variables in (12)–(16) are shown in Fig. 9. Direct kinematic equations can be simplified in this case (cf. also Fig. 9):

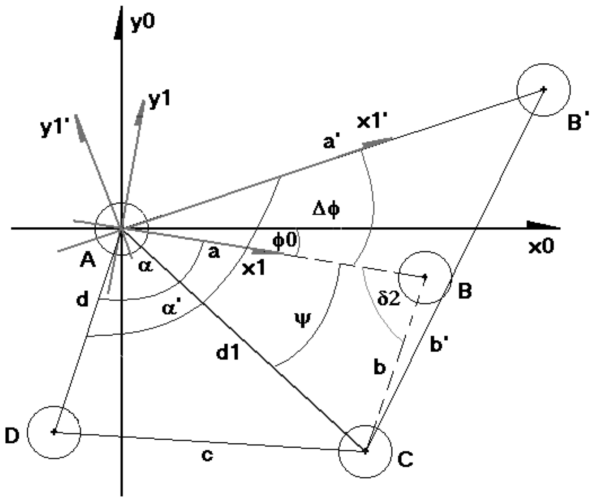

Fig. 9. Kinematic description of the displacement of the second leg

$$\Delta\varphi = \alpha' - \alpha, \tag{17}$$

$$x_{B1} = a', \tag{18}$$

$$y_{B1} = 0. \tag{19}$$

3. The displacement of the third leg from C to C' is shown in Fig. 10. The inverse kinematic equations, with known x_{C1} and y_{C1}, have the following form:

$$\psi = \operatorname{atan2}(-y_{C1}, x_{C1}), \tag{20}$$

$$d_1' = \sqrt{x_{C1}^2 + y_{C1}^2}, \tag{21}$$

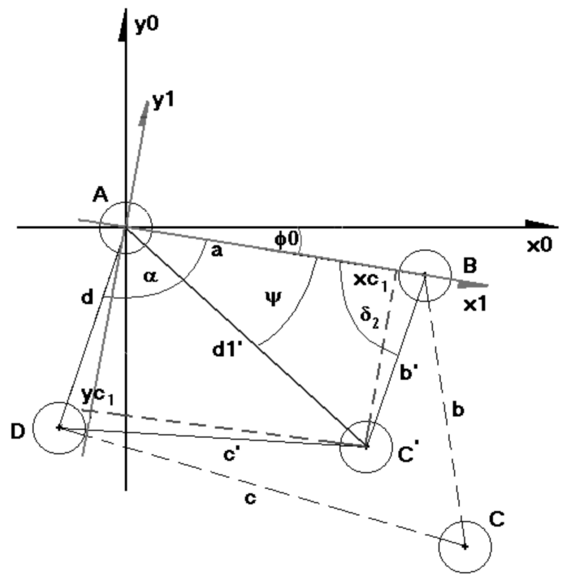

Fig. 10. Kinematic description of the displacement of the third leg from C to C'

$$b' = \sqrt{d_1'^2 + a^2 - 2d_1' a \cos\psi}, \tag{22}$$

$$c' = \sqrt{d^2 + d_1'^2 - 2dd_1' \cos(\alpha - \psi)}. \tag{23}$$

As before, all variables in (20)–(23) are shown in Fig. 10. The direct kinematic equations in this case are as follows (cf. Fig. 10):

$$\sin\psi = \frac{b \sin\delta_2}{d_1'}, \tag{24}$$

$$\cos\psi = \frac{a^2 + d_1'^2 - b'^2}{2ad_1'}, \tag{25}$$

$$x_{C1} = d_1' \cos\psi, \tag{26}$$

$$y_{C1} = d_1' \sin\psi. \tag{27}$$

4. The displacement of the fourth leg from D to D' is shown in Fig. 11. The inverse kinematic equations, with known x_{D1} and y_{D1}, have the following form:

$$\alpha' = \text{atan2}\left(-y_{D1}, x_{D1}\right), \tag{28}$$

$$d' = \sqrt{x_{D1}^2 + y_{D1}^2}, \tag{29}$$

$$d_1 = \sqrt{a^2 + b^2 - 2ab\cos\delta_2}, \tag{30}$$

$$\sin\xi = \frac{b\sin\delta_2}{d_1}, \tag{31}$$

$$\cos\xi = \frac{a^2 + d_1^2 - b^2}{2ad_1}, \tag{32}$$

$$\xi = \text{atan2}(\sin\xi, \cos\xi), \tag{33}$$

$$c' = \sqrt{d'^2 + d_1^2 - 2d'd_1\cos(\alpha' - \xi)}, \tag{34}$$

and the direct kinematic equations can be simplified in this case (see Fig. 11):

$$x_{D1} = d' \cos\alpha, \tag{35}$$

$$y_{D1} = -d' \sin\alpha. \tag{36}$$

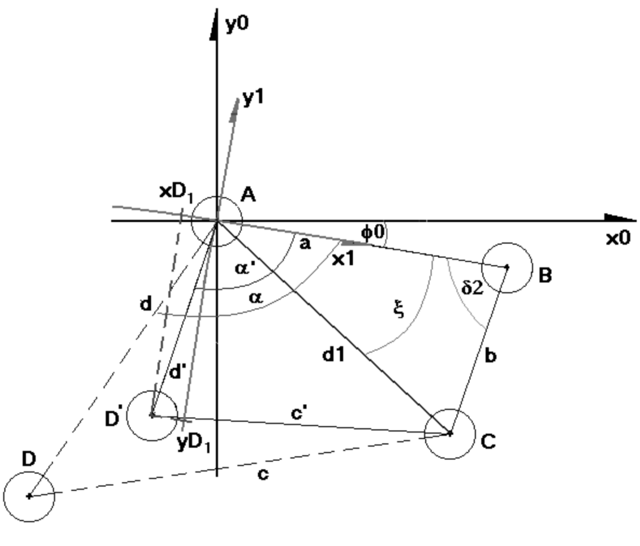

Fig. 11. Kinematic description of the displacement of the fourth leg from D to D'

Let us notice, that positions of the second, third and fourth legs are expressed in the coordinate frame attached to the first leg. Therefore for the first leg the increments Δx and Δy are used, as in formulae (9) and (10). The other leg coordinates are defined in the reference frame (depending on the new position of the first leg) — see: (18), (19), (26), (27), (35), (36).

The calculations of the direct and inverse kinematics, described by formulae (1)–(36), make use of the measurement results obtained from the sensors placed on the robot board: the incremental encoders mounted on the motor shafts and the potentiometers for measurement of absolute configuration angles. Additionally, the control system receives information about the robot orientation in global coordinates.

The following quantities are measured in the mechanical system:

- lengths of the sides of the sliding frame,
- angles between these sides,
- lengths of the legs,
- the force fastening the suction cup to the ground.

Positions of the suction cups relative to the reference frame, attached to the first foot (A), are calculated taking into account current values of the measured quantities. Position of this frame is specified relative to the base coordinate frame attached to the wall of the building.

In case of the inverse kinematics problem, the new position of the first foot is defined with use of the increments Δx and Δy. For other legs the target position in the reference frame attached to the first foot is known. Moreover, the sequence of leg displacements is defined.

It is worth to notice, that the z coordinate (lifting of the leg) is not taken into account in kinematics calculations. Namely, the z coordinate results from the condition of reaching the desired tightening force to the wall and, as as a consequence, it depends on the surface of the wall. When the sliding frame is is too close or too far from the wall, the control system corrects simultaneously the leg lengths.

4. On-board Strus manipulator

The Strus manipulator is mounted at the front part of the Safari mobile platform. It is capable of making elementary diagnostic/repair tasks on building walls. This manipulator has five degrees of freedom, driven by DC motors. It is designed for precise operation of objects weighing less than 2kG (the weight of the manipulator without load is equal to 5kG). Figure 12 shows the kinematic performance of the Strus manipulator.

The radius of its workspace is about $0.5m$. The dynamics of the manipulator can be neglected because accelerations and velocities of the manipulated objects should not be too large. The manipulator has five degrees of freedom. It is assumed that the axis of the tool is perpendicular to the wall. The first three kinematic

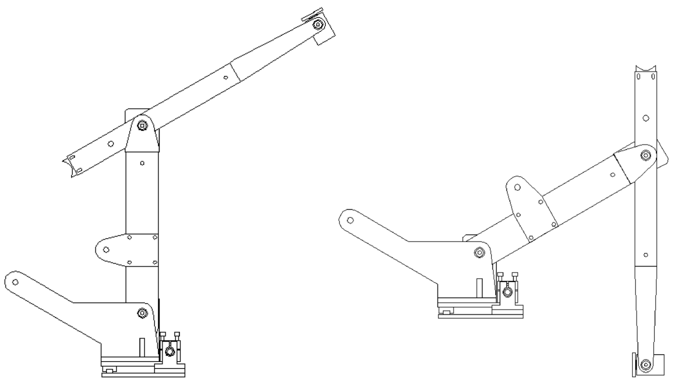

Fig. 12. STRUS manipulator in two extreme configurations

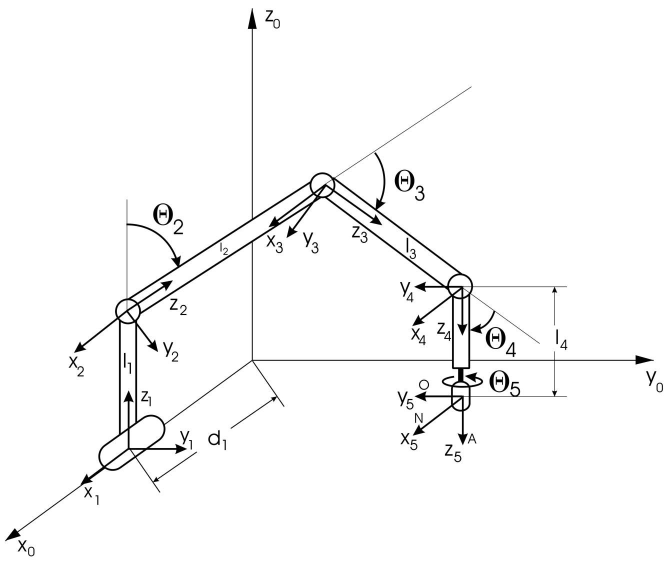

Fig. 13. Kinematic parameters and coordinate frames of the STRUS manipulator

pairs are driven by linear drives, while the first joint is prismatic and the others are rotational. The kinematic parameters of the STRUS manipulator and the assignment of coordinate frames to particular links are shown in Fig. 13.

Because of construction limitations, the ranges of configuration coordinates are significantly reduced (see Table 1).

Assuming that the orientation of the gripper (link N) is the same as that of the fifth coordinate frame, the solution of the direct kinematic problem is as described by Eq. 37 (for notation see Fig. 13): where $s_{234} = \sin(\Theta_2 + \Theta_3 + \Theta_4)$, $c_{23} = \cos(\Theta_2 + \Theta_3)$, etc.

The solution of the inverse kinematic problem for known ${}^0_NT$ matrix consists of finding d_1, Θ_2, Θ_3, Θ_4 and Θ_5, and in this case is relatively easy provided that the ${}^0_NT$ matrix is attainable for the tool mounted on the STRUS 5dof manipulator.

The controllers of all the DC motors are based on the AT89C2051 microcontroller. To increase the precision of manipulator position measurement, the incremental encoders in quadrature mode are used.

Table 1
Ranges of configuration coordinates of the STRUS robot

Variable	Range of values
d_1	$\langle 0, 0.275\rangle$ [m]
Θ_2	$\langle 0, 58\rangle$ [°]
Θ_3	$\langle 62, 118\rangle$ [°]
Θ_4	$\langle -90, 90\rangle$ [°]
Θ_5	$\langle -180, 180\rangle$ [°]

5. Sensor system

The SAFARI robot is constructed for moving on vertical panels of uneven surfaces. Therefore a sufficient adhering force has to be applied, to fix the robot's mobile platform to the surface on which it moves. Furthermore, it is indispensable to measure an instantaneous value of this force, to prevent the mobile part from falling off from the vertical movement plane. Since the surface on which the robot moves in our application is rough and local obstacles might occur on the robot's path, the mobile platform is supported on four legs, perpendicular to the surface and ended with sets of suction cups. These suction cups have to ensure a sufficient adhering force, holding the mobile part of the robot on a vertical panel. Due to the fact that the texture of the movement surface may be porous (e.g. concrete or plaster walls), it is impossible to develop required adhering force using popular, high-underpressure suction cups. Therefore, in order to achieve fairly large adhering force, we propose to use large-area suction cups, working with low underpressure but with large airflow. Such suctions can ensure quite large fixing forces, even if there is no tight seal between the suction and the surface, on which the suction is placed. However, on smooth surfaces (e.g. metal or painted walls) high-underpressure suction cups are sufficient for providing the required fixing force, preventing the mobile platform from falling off. As a consequence, in our application we use both types of suction cups in each leg: three of small-area,

$$
{}^0_NT = \begin{bmatrix} c_5 & -s_5 & 0 & x_Nc_5 - y_Ns_5 + d_1 \\ c_{234}s_5 & c_{234}c_5 & s_{234} & (x_Ns_5 + y_Nc_5)c_{234} + (z_N + l_4)s_{234} + l_3s_{23} + l_2s_2 \\ -s_{234}s_5 & -s_{234}c_5 & c_{234} & -(x_Ns_5 + y_Nc_5)s_{234} + (z_N + l_4)c_{234} + l_3c_{23} + l_2c_2 + l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (37)
$$

high-underpressure type and one of large area, low-underpressure but large-airflow type, which encloses the small ones (one large high-airflow suction covers three small ones per each leg).

To calculate the instantaneous value of the force fixing the robot to the vertical surface, it is necessary to know the value of underpressure in each of the suction cups and their areas. Therefore, the first important element of the Safari robot's sensor system is an underpressure measurement circuit, delivering information about the difference between the atmospheric pressure and the pressure in each of the suction cups. Here we propose to use relative pressure sensors, developing output voltage proportional to the pressure difference. Each of the pressure sensors consists of four piezoresistant elements, forming a bridge. When supplied with 1.5mA current source, output sensitivity of 0.1mV/mbar is obtained. This is because using current source eliminates errors induced by supply voltage drift, occurring when voltage source is used. The full-scale range of the pressure sensors is ± 1 bar, with transient overload of ± 2 bar allowed. The output voltage, formed and amplified by instrumentation amplifiers, is then converted to a digital signal by an A/D converter, built into a microcontroller. A single microcontroller controls pressure sensors connected to three small suctions of a single leg. Separate sensor elements are used for measuring underpressure in large-airflow suction cups; such solution gives the possibility of using different types of suction cups (high- and low-underpressure) separately, depending on the type of the surface, on which the robot moves.

During its movement, the robot may come across small ledges of the surface. In order to place a robot leg on such a ledge, or to go over it, it may be necessary to know the actual distance from the end of the leg to the surface. To perform such measurement, a low cost optical sensor is attached to each leg. The output signal of an analog infrared distance sensor, used in our application, is inversely proportional to the distance.

On the surface the robot moves on, a number of small cracks and slots may exist. It is therefore not always possible to place firmly a leg on the surface. In order to verify whether the leg has stable contact with it, up to eight microswitches (or other open-close sensors) are installed around the set of suction cups of each leg. A typical switch makes multiple transitions during tens of milliseconds while opening or closing. In addition to this phenomenon, known as 'bouncing', switches and digital systems have other unexpected behaviour, manifesting, for example, when switch wiring is placed in a noisy industrial environment. An open switch has very high impedance by definition, so interfering signals cannot corrupt their work. However, any noise impulse, capacitively or inductively coupled with the switch wiring, can cause phantom switch closures. In order to reduce the effects described, the binary signals coming from the switches installed around the suction cups are input to a special 'debouncing' circuit.

Each of four Safari robot legs is equipped with the following set of sensors:

- three piezoresistant underpressure sensors,
- up to eight microswitches,
- infrared optical distance sensor,
- additional temperature sensor for thermal compensation of underpressure sensors.

Another important feature is to have the opportunity to control the orientation of the mobile platform in relation to the movement surface. If the surface is strictly vertical (parallel to the Earth's gravity field vector), static accelerometers may be used to determine the angle between the robot's platform and the movement surface. Therefore an additional sensor is used in the Safari robot system — a digital inclinometer. Here we use two double-axes digital accelerometers ADXL202. Those devices, available in the form of small integrated circuits, are build as electronic micromachines, containing small silicon inertial elements, deflecting under applied acceleration. This deflection is represented by voltage difference, developed inside the circuit and compared with an internal voltage reference source. The voltage difference is then converted into a PWM square wave, appearing on the chip's terminals and measured by a microcontroller, supervising the accelerometer's work. A single ADXL202 chip gives information about accelerations acting along two perpendicular axes X and Y. The values of acceleration are proportional to the duty cycle of the output signals (PWM). By placing two ADXL202 circuits such that their X or Y axes are parallel while the remaining two axes are perpendicular to each other, we have the opportunity to measure X, Y and Z components of acceleration acting in 3-D space.

As mentioned above, to control the position of the robot's mobile platform it is necessary to know how far each leg is pulled out along the axis perpendicular to the plane on which the robot moves. Information about the lengths of linear drives, used for positioning the legs, is also essential. In the Safari robot, linear movement is achieved by usage of linear drives with ball screws. The screws are driven by DC motors and timing belts, so the easiest option for determining the linear drive pull out is to use incremental encoders, installed on the motor shafts. Knowing the transmission ratio of timing pulleys, thread diameter and pitch, it is possible to determine the position of the linear drive, assuming that the number of motor rotations is known. Consequently, the sensor system has to be extended with digital encoders, indicating angular positions of the driving motors.

Considering the tasks for the Safari robot, an important element of the sensor system is a vision subsystem. Such equipment is thought to be mostly used for observation of the environment, in which the robot operates. The main element of the vision system is a Convision V600

videoserver, which tasks are:
- acquisition of image frames, coming from the cameras mounted on the robot's platform,
- conversion of analog PAL video signal into digital frames,
- compression of the frames using JPEG format, in order to reduce the size of pictures,
- sending digitized frames as video stream via Ethernet LAN to visualization stations (e.g. operator console).

Convision V600 is a device originally designed for use in surveillance systems; it has some additional peripherals built in, which may also be useful on the SAFARI robot's board. Those components are: two-state inputs and outputs (relays and switching transistors) and two RS-232 compatible serial ports. These accessories may be used e.g. for positioning the on-board cameras. Access to this equipment is made in the same way as to video data, i.e. via the HTTP protocol. Data exchange between the videoserver and the remaining parts of the Ethernet network, which the device is connected to, is carried out via TCP/IP protocols at 10-Mbits per second rate with UTP (Unshielded Twisted Pair) cable used as a transmission medium.

Since it is possible to connect up to six video sources to the video server, some cameras mounted on the mobile platform may be used by the robot itself to detect obstacles in the surroundings where the robot operates. The detected obstacles may be taken into consideration by a path planning algorithm, implemented on the embedded computer installed on the mobile platform.

6. Software control system

The control software of the SAFARI robot is supervised by the RTLinux ver. 3.1 real-time operating system based on Mandrake 2.4.4. Its inspection, measurement and supervisor/acquisition systems [13,14] are distributed, flexible and easy to extend. In our case, the software system implementation of the control/acquisition system of the climbing robot is presented in Fig. 14 and consists of the following elements:
- software of the host industrial computer (a PC computer with the real-time operating system), placed at the robot's body,
- control system for the actuating units (microcontrollers) responsible for manipulation and locomotion of the robot,
- software of the measurement systems of the robot (measuring position, pressure, temperature, distance, etc.),
- tasks of system inspection (cameras connected via the video server, ultrasonic devices, special devices for particular tasks),
- software of spare control system of the climbing robot mirroring the host computer to improve its reliability,
- main control/acquisition console (a PC computer) for a person supervising the system.

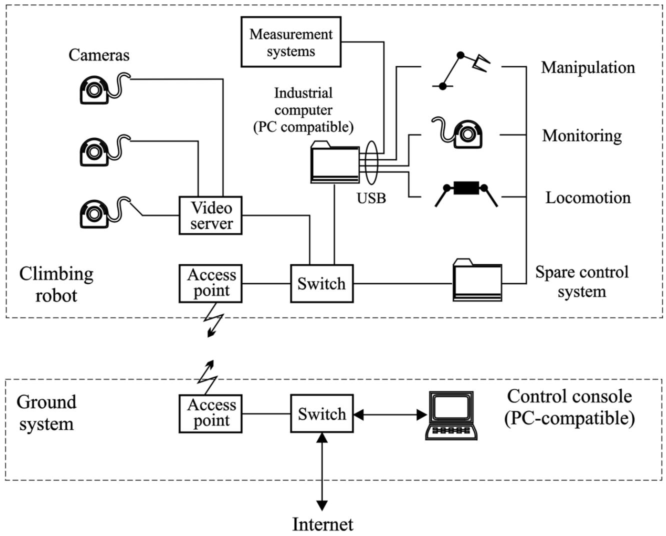

Fig. 14. Control system of the climbing robot

Connection of the console and the climbing robot is implemented via Ethernet. There are special network devices on the robot, called 'access points', in the wireless (radio) version. All devices working in the local network of the robot are connected to a switch, which is connected directly to the 'access point'. The local network of the robot consists of an industrial miniature control computer (PC-class with RTLinux), a spare control system (mirroring computer), and a vision server. The industrial computer is connected to intelligent actuating/mesurement devices via Universal Serial Bus or RS485. The microcontrollers are connected to the network using special techniques from local industrial networks. To make the system secure and reliable, in case of failure of the host computer, it is automatically replaced by a spare control system which gives the console access to actuating devices and, e.g. the robot control may be switched to the manual mode.

The control console, placed on the ground, is also equipped with an 'access point' connected via switch and working under popular Linux operating system (or Windows 2000). It enables communication between the console and the climbing robot and other local computers as well as connection to a wide area network (WAN).

Software organization assures using multiple channels of data interchange between objects responsible for particular tasks. Channels are elements of data streams, which are generally of two types: the stream of control information (mainly from the console to the climbing robot) and the stream of measurement data directed mainly to the console (state of the robot and special measurements). Each element of the software system is implemented as an agent-an object equipped with plug-ins, which can pass signals from outside causing execution of some operations inside the object. The object gives access to a predefined set of plug-ins. The signal is described by a protocol consisting of the name of the action and parameters. All objects can pass messages to other objects and receive a response. Objects know only interfaces, i.e. plug-in sets with protocols [13,15]. Particular object implementations can be done in any programming language and any software/hardware platform, which enables using the CORBA standard.

The operator at the control console (placed on the ground) supervises work of the whole system. There are following ingredients of the software system, resident on the control console (see Fig. 15):

1. Working desktop of the STRUS manipulator, which enables control of the manipulator mounted on the mobile platform.
2. Trajectory planer, designed for path planning for the SAFARI robot.
3. Visualisation module, giving the operator direct access to real task environment, surroundings of the robot, its current position and orientation relative to the wall, enabling robot movement tracking.
4. Supervising module of the control console (control of flow of data coming from various applications, which is a condition of fluent transmission between the mobile platform modules and the control console).
5. Vision correction module correcting discrepancy between current and virtual position/orientation on the wall of the robot.

The following software modules are implemented on the platform board computer (see Fig. 15):

1. Manipulator control algorithms module, which — cooperating with the working desktop — enables control of the board manipulator (sends current position and orientation of the manipulator to the control console).
2. Module of the mobile platform movement control, which — using reference values of displacements — solves the inverse kinematic problem and uses the results for correct control of leg movements.
3. Module supervising locomotion function of the robot (of mobile platform control algorithm) and enabling communication between the layers of the control subsystems.
4. Sensoric communication module, which contains implementation of commands recognized by the sensoric subsystem.
5. Measurement module, which is responsible for measurement of physical values and is connected with the sensoric communication module.
6. Diagnostic module TINI, which takes over control of the mobile platform and enables alternative connection with the control console in case of system breakdown.
7. Robot supervising module, which enables monitoring of the measurement subsystem and, on the basis of information coming from this subsystem, estimates current state of the robot.

The software system has an open architecture made of several modules, with well defined communication between them. It can be easily extended by adding extra modules which will be necessary to incorporate some specific measurement for the purpose of diagnosis.

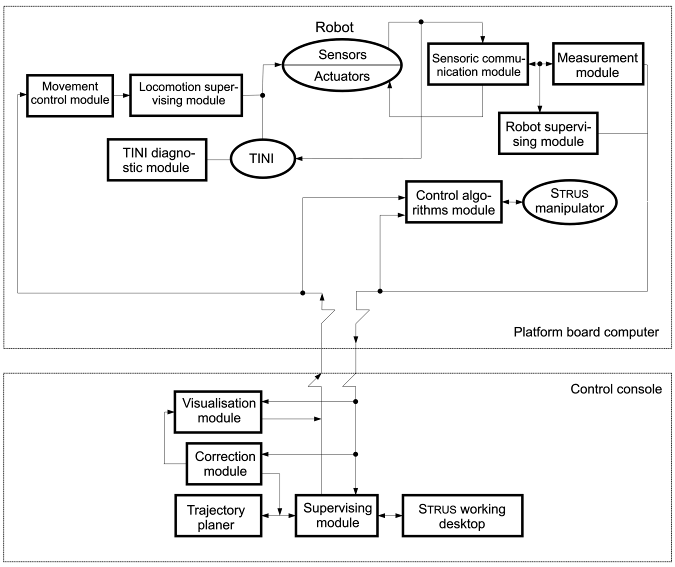

Fig. 15. Software structure of the climbing robot

7. Conclusions

In the paper, the SAFARI inspection robot, which can be applied for building inspection, has been presented. The mechanical and control structures have been outlined. Description of the sensor system, necessary for determining robot's state and controlling its subsystems, has also been included. Moreover, SAFARI kinematics and movement strategy have been characterized. Information flow scheme of the system and data exchange between the mobile and stationary subsystems of the robot have been illustrated.

The SAFARI is a unique construction of this kind in Poland. In design, modern prototyping tools and advanced knowledge from areas of electronic and programming technology have been used. An important result of the research is that, besides of this work, the research team has earned a lot of experience, which is necessary to design similar inspection robots.

Several laboratory tests of the SAFARI climbing platform have been carried out with repeatable, positive results. There are plans to put the robot to practice in several applications after necessary modifications. Further research will be focused on adaptation of the SAFARI or similar constructions for other inspection applications (for example inspection of pipes in special channels, etc.). Information from the sensor system via a wide-area network in connection with visualization of the data obtained from the on-board sensors is necessary for such tasks. Therefore, this thread will be intensively developed.

References

[1] C. Canudas de Wit, B. Siciliano and G. Bastin, *Theory of Robot Control*, Springer-Verlag, Berlin, 1996.

[2] K. Kozłowski, P. Dutkiewicz and W. Wróblewski, *Robot Modelling and Control*, Polish Scientific Publishers PWN, Warsaw, 2003, (in Polish).

[3] K. Tchoń, A. Mazur, I. Dulęba, R. Hossa and R. Muszyński, *Manipulators and Mobile Robots. Models, Motion Planning, Control*, Academic Publishing House PLJ, Warsaw, 2000, (in Polish).

[4] 4 D. Dobroczyński, P. Dutkiewicz, P. Herman and W. Wróblewski, "A climbing robot SAFARI for buildings inspection", *Proc. of the 4th International Conference on Climbing and Walking Robots 'CLAWAR'*, pp. 937–944, Karlsruhe, (2001).

[5] D. Dobroczyński, P. Dutkiewicz and W. Wróblewski, "Climbing robots in context of walking robots control", *Studies in Automation and Information Technology* 26, 27–44 (2001), (in Polish).

[6] T. Szypiło, "Control algorithms of walking robots", *M.Sc. Thesis*, Poznań University of Technology, Poznań, 2000, (in Polish).

[7] 7 S. Hirose and K. Kawabe, "Ceiling walk of quadruped wall climbing robot Ninja", *Proc. of the 1st Int. Symposium 'CLAWAR'*, 143–147 (1998).

[8] A. Nagakubo and S. Hirose, "Walking and running of the quadruped wall-climbing robot", *Proc. of the IEEE International Conference on Robotics and Automation*, 1005–1012 (1994).

[9] M. Prieto, S. Marmada and J.C. Grieco, "Experimental issues on wall climbing gait generation for a six-legged robot", *Proc. of the 2nd Int. Symposium 'CLAWAR'*, 125–130 (1999).

[10] G. Muscato and G. Trovato, "Motion control of a pneumatic climbing robot by means of a fuzzy processor", *Proc. of the 1st Int. Symposium 'CLAWAR'*, 113–118 (1998).

[11] 11 P. Dutkiewicz and M. Ławniczak, "Sensor system for SAFARI wall-climbing robot", *Archives of Control Sciences* 12(1–2), 103–123 (2002).

[12] P. Dutkiewicz, M. Kowalski, M. Ławniczak and M. Michalski, "SAFARI inspection robot motion strategy", *Proc. of the 3rd International Workshop on Robot Motion and Control (RoMoCo'02)*, Bukowy Dworek, Poland, 93–100 (2002).

[13] D. Dobroczyński, P. Dutkiewicz and W. Wróblewski, "Software system of the climbing robot", *Studies in Automation and Information Technology* 25, 71–82 (2000), (in Polish).

[14] 42 K. Kozłowski, P. Dutkiewicz, M. Ławniczak, M. Michalski and M. Michałek, "Measurement and control system of the climbing robot SAFARI ", *Proc. of the 5th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, pp. 1003–1012, Paris, (2002).

[15] "Common object request broker: architecture and specification". *Object Management Group*, Revision 2.3. http://www.omg.org