MESSOR - VERSATILE WALKING ROBOT FOR SEARCH AND RESCUE MISSIONS

Submitted 17th June 2010; accepted 22nd December 2010.

Krzysztof Walas, Dominik Belter

Abstract:

Nowadays there are more people living in the cities than in the countryside. With the growing number of multi-storey buildings, which are built very fast, the number of possible collapses is rising. Rescue missions in ruins of such constructions pose a possible threat to the life of the rescuers. To avoid involving people in such missions mobile robots are used. The use of a six-legged robot in Urban Search and Rescue missions is proposed due to its static stability while walking on rough terrain. In this paper six-legged walking robot Messor is described. Its mechanical structure was designed in such a way, that negotiating obstacles met in urban space is possible. In order to perform such tasks as walking over rough terrain or climbing stairs the robot is equipped with significant number of on-board sensors. The control algorithms, which take advantage of mechanical structure were developed. At the beginning a mechanical structure of the robot is described. Next, the design of the robot control system architecture is considered. Then the robot sensory system is presented and afterward the application software is characterized.

Keywords: *walking robot, six-legged, field robots.*

1. Introduction

Fig. 1. The Messor robot.

Urban areas are getting bigger each day. Nowadays there are more people living in the cities than in the countryside. With the growing number of multi-storey buildings, which are built very fast, the number of possible collapses is rising. Rescue missions in ruins of such constructions pose a possible threat to the life of the rescuers. To avoid involving people in such missions mobile robots are used. The use of a six legged robot in Urban Search and Rescue missions (USAR) is proposed due to its static stability while walking on rough terrain.

Six-legged robots and their use in the field missions is a very popular research topic, thus many such robots have been built in a last few years. Some of them were built to perform specialized function such as demining missions. The prototypes were built in Japan [15] and in Spain [8]. Other robots are used for example as a planetary rovers [13]. There were also some multipurpose robots: Lauron III [7] and Scorpion [10] which is in fact an eight-legged robot but its design is similar to a six-legged robot. Some other experimental examples are: the robot which is equipped with piezoceramic actuator [19], and the DLR-Crawler [9], which structure is based on the fingers of DLR-Hand II [6].

In this paper the six-legged walking robot Messor is described. The robot is aimed to work in USAR missions. Its mechanical structure was designed in such a way that negotiating obstacles met in urban space is possible. In order to perform such tasks as walking over rough terrain or climbing stairs the robot is equipped with significant number of on-board sensors. The control algorithms, which take advantage of mechanical structure, and are supported by the use of appropriate sensors, were developed. The robot is shown in Fig. 1.

The paper is organized as follows. At the beginning a mechanical structure of the robot is described. Next, robot control system architecture problem is considered. Then the robot sensory system is presented and afterwards the application software is characterized. Conclusions and future work plans are provided at the end.

2. Mechanical structure of the robot

The Messor robot is the second generation prototype of the six-legged walking robot which was built in our institute where the research on mobile robotic have been conducted since 1990. The first one was the Ragno robot. The kinematics, sensory system and control of this robot is described in [3], [16]. Design of the robot Messor is based on the experience acquired during the development of the first generation machine. Its kinematic structure is thus similar to the previous prototype, only the dimensions were changed. This new mechanical design allows the robot to perform more demanding locomotion tasks.

2.1. Robot trunk

Messor and its trunk are designed to fulfill two requirements. The first is about the distribution of the forces on the robot legs during the tripod gait on flat surface. The leg-end forces should not differ much. The second requirement addresses the dimensions of the trunk to enable the robot to climb the stairs.

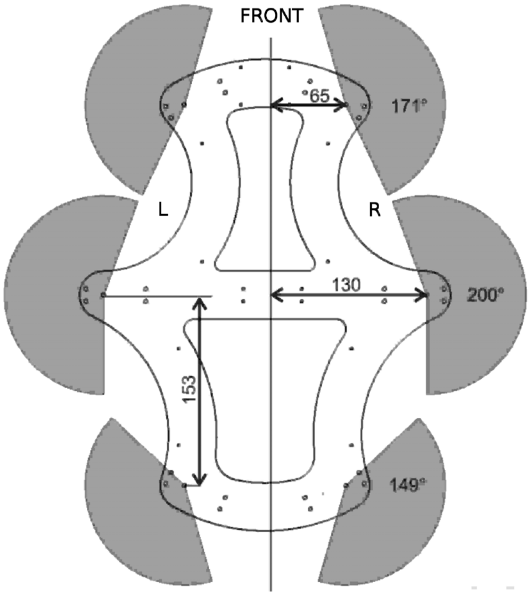

Fig. 2. Trunk of the robot with the workspace for the first joint marked.

The equal distribution of the forces was found by using the balance of the forces and torques on the robot trunk. The point of the attachment of the middle legs to the trunk was found by calculations. The distance of the assigned point is further from the vertical axis of the trunk twice the distance of front and hind legs of the robot. The trunk of the robot Messor is shown in Fig. 2. The same solution for the design of the trunk was adapted in the robot for demining missions which was described in [8].

The first requirement implied the bounds on the horizontal dimensions. The vertical dimensions were chosen in order to enable standard stairs climbing. For this purpose the dimensions of the stairs were investigated. The depth d of the stair and the height h of the stair should be in relation $60 < 2 \cdot h + d < 65$ cm. The formula comes from the technical regulation concerning the structures built in Poland. The highest possible stair in habitable building is 20 cm which gives the depth of 20 cm while assuming the lower limit. Due to the posed requirement on the minimal depth of the step, the distance between two pairs of legs is 15.3 cm to enable the robot to put two pairs of the legs on the same step.

2.2. Robot leg

The kinematic configuration of the leg is similar to an anthropomorphic robot arm. It has 3-DOF, so only position control is available but not the orientation of the tip. The segments of the legs have the following dimensions: coxa 5.5 cm, femur 16 cm, tibia 23 cm (with the foot), which corresponds approximately to the proportions of the insects leg segments met in the nature. The proportion for the insect is 1:4:5. This proportion was the starting point in the design process. In order to obtain geometrical dimensions of the leg at least the length of one segment has to be established. Thus, the length of the distal part of the leg was found according to the requirement posed by the stair climbing strategies. As the highest possible step is 20 cm, so the distal segment of the leg is 23 cm long. The additional 3 cm eases the negotiation of the stairs.

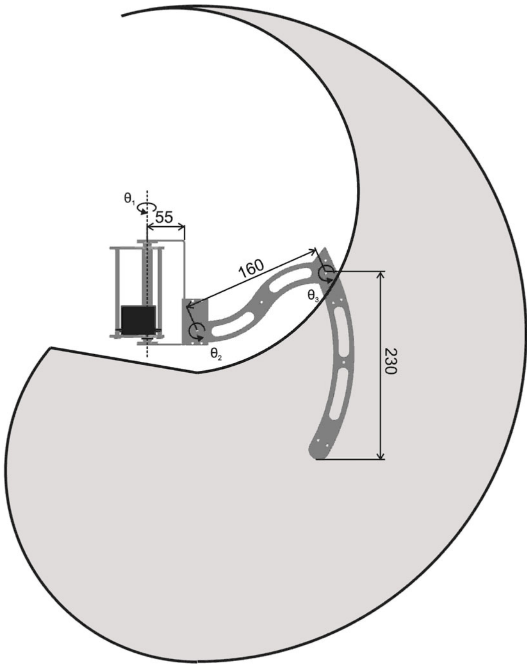

Fig. 3. Robot leg and frontal cross section of its workspace.

Let's look at the working area of the single leg. The kinematic structure of the robot leg is shown in Fig. 3. In the first joint (nearest to the trunk) the movements are constrained by the structure of the robot. For forelegs the available angle of the movement is 171°, for the middle legs is 200°, and for the hind legs is 149°. The angular ranges of movements for the first joint of each leg are shown in Fig. 2. As it could be seen the robot is able to rotate its fore and hind legs in order to assume a mammal like configuration of the legs and is able to walk on four legs. Regarding next two joints, the cross section of the working area is shown in Fig. 3. The mobility is limited in the top part of the area, above the robot. So the Messor is not able to walk while turned upside down, but the area of possible movements beneath the robot is large. It creates the possibility of hiding the legs under the trunk or grasping an object with the legs. This ability combined with the one mentioned earlier enables the robot to carry some limited load held by middle legs, and performing the mammal like walk on four legs i.e. on front and hind legs.

2.3. Actuators

The Messor robot is equipped with robotic servomotors. Each of them provides 2.94 Nm of torque, 38.5 W of power, and its mass is only 68 g. The motors have a digital interface (Hitec HMI protocol) with the position control. The used motors enable the robot to walk efficiently on the rough terrain, and to climb obstacles. The smooth change of the speed of the robot movements is possible.

3. Sensory system

The Messor robot is equipped with many sensors which could be divided into two groups. One group of sensors is responsible for safety of the walking procedures on a rough terrain. The second group is more sophisticated and is used for path planning.

3.1. Sensors used for the safety of walking

To perform safe movement of the robot from one location to another, the information about its pose as well as on contacts of its feet with the ground is needed.

The pose of the robot is estimated by using a 6-DOF Inertial Measurement Unit (IMU). The module consists of three accelerometers and three gyroscopes. Each accelerometer provides data about the robot acceleration along each axis of the local coordinates frame, while the gyroscopes provide the information on the angular velocity of the robot around each axis of the local coordinates frame. These data allow to stabilize the platform of the robot during steepness climbing as well as to correct the heading while walking.

As to sensing of a contact of the robot feet with the ground two types of sensors were used. The first one is mounted at the tip of the foot and provides information on the contact force with the ground. It is a resistive sensor, where the resistance is decreasing with the increase of the contact force. According to the drop of the resistance the voltage on the resistor is rising. The voltage is measured by the microcontroller equipped with an A/D converter. The data are used for sensing contacts with the ground.

Another part of the system is a current sensor attached to each motor of the leg. The information of the current in each leg enables the calculation of the torque in each joint and then to apply equation:

$$F=(J^{T})^{-1}Q \qquad (1)$$

where,
F - reaction force vector [3x1],
J - geometric Jacobian for the leg [3x3],
Q - torque in each joint vector [3x1].

In that way force exerted on the ground at the tip of the leg is obtained.

The simultaneous measurements from the two above mentioned sensory systems fixed on the leg provides a reliable information about the contact with the ground. These measurements are also used to sense the surrounding environment and enables to implement simple reactions scheme in case of the occurrence of unexpected or unperceived obstacles.

The robot can also be equipped with any kind of chemical substances sensors. The sensors should have resistance or voltage output. In our experiments the robot is equipped with ethanol sensor.

3.2. Sensors used for the path planning

Search and rescue missions are performed in very rough terrain so good path planning is needed in order to perform mission. The Messor robot is equipped with three main sensors for mission support.

The first one is the video camera uEye - UI-1225LE-C which gives information about the surrounding environment and it is used in the Simultaneous Localization and Mapping (SLAM) subsystem and also for visual odometry. The model used on the robot has a picture resolution 752x482 and frame rate 87 fps. The robot uses monocular vision system.

The second one is the Laser Range Finder (LRF) Hokuyo URG-04LX. Its performance is described in [14]. The sensor is used for map building. The surface in front of the robot is scanned while walking. Resolution of the elevation map is constant [5]. The scanning time for the LRF is equal to 100 ms. The elevation map is built on-line and is used in algorithms for searching the stable candidate contact points and for path planning. The robot changes the body attitude while walking. At each point along the trajectory the robot stops the movement and makes scan.

In the case of climbing obstacles a different approach to map building has to be used. In such a mode the robot stops before the obstacle and performs a scanning movement. The model of the whole object is built and the robot is able to plan the climbing strategy in advance. This approach is possible because climbing is rather a deliberative process.

The third sensor and auxiliary one is the structural light system. It is the vertical laser stripe which is used for stair climbing control in order to measure a stair depth and height. The use of the structural light involves the use of the camera. Thus other vision based algorithms couldn't be performed at the same time.

4. Robot control system architecture and hardware configuration

4.1. Logical architecture

The robot is a complex system with 18 servomotors and a number of sensors on board. The logical architecture and device configuration should be adjusted to the mechanical structure and applications of the robot [11], [12]. The control system architecture should be organized to provide the appropriate resources for each functional module of the control system. To guarantee the real-time operation and high-performance all components work simultaneously. The robot control system provides the response of the servomotors without significant delays and allows to measure the state of the robot during the movement (orientation of the robot's platform, real angles in servomotors, current in motors), simultaneously operate low-level, fast control-loops and modules which demand a lot of computational resources.

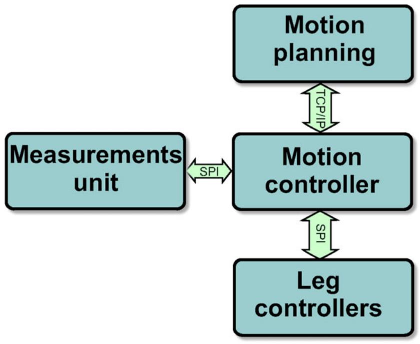

Fig. 4. Robot control architecture scheme.

The robot control system architecture is hierarchical and it is divided into four layers (Fig. 4):

- mission control (e.g. motion planning),
- motion control,
- leg measurements and control,
- environment sensing.

The main tasks for the top layer are: terrain mapping, self-localization, visual odometry and motion planning. To perform these assignments appropriate computational resources and high-level algorithms are necessary. The output of the algorithms are movement orders which are sent to the middle layer of the control system. The modules which are located in the top layer can also send queries to the middle layer asking about the present state of the robot. The top layer enables also the communication with the teleoperator and the transmission of the camera images to the remote control center. In the opposite direction only the movement orders are sent.

The middle layer is responsible for the motion control. To execute the desired movement the appropriate software module computes the reference values for the servomotors and sends them to the legs controllers. To deal with the robot kinematics the calculus unit with floating point operations is necessary. The most important feature of this layer is a fast and reliable communication module. It allows to send desired values to the leg controllers and to read the data from sensors during the movement. This communication should be faster than the reaction of the servomotors. It allows to modify the desired values and read current angles in robot joints in dynamic states.

The bottom layer consists of a measurement unit and of six controllers (one for each leg). The modules which are located on this layer are responsible for the cooperation with the sensors and the actuators. The leg controllers receive the reference values for the legs joints and resend them to the appropriate servomotors. It provides an appropriate interface between the number of various electronics devices and the higher layer which is responsible for the computationally demanding tasks. The controllers also receive and collect information about the measured legs angles, contact forces and currents of motors. The measurement unit is responsible for conditioning the signal from the on-board sensors of chemical substances and from the IMU.

4.2. Device configuration

The device configuration of the robot is shown in Fig. 5. The top layer of the control system is located on the Single Board Computer. The robot is equipped with the PICO 820 computer with Intel Atom on board. It uses Linux operating system to manage devices. The computer communicates with the teleoperation device through the Bluetooth or WiFi channel. The camera and laser range finder are plugged into the USB ports of the Single Board Computer.

The motion controller is located on a board with the EP9302, ARM9 core microprocessor. It computes the desired values for the servomotors. The microprocessor supports the fast floating point arithmetic operations on homogeneous transformation matrices. It is energy efficient and supports a high-level embedded operating systems such as Linux. The applications for EP9302 can be prepared in the majority in the high-level programming languages which makes the microprocessor programming easy.

The lowest layer of the control system is based on the AT91SAM7S256 microcontrollers with 32-bit ARM7 core. Its peripherals include UART ports, SPI communication channels, 10 bit analog to digital converters, timers, DMA controllers and interrupts management unit. It also supports floating point operations, which are very useful in signal preprocessing. There are six microcontrollers on-

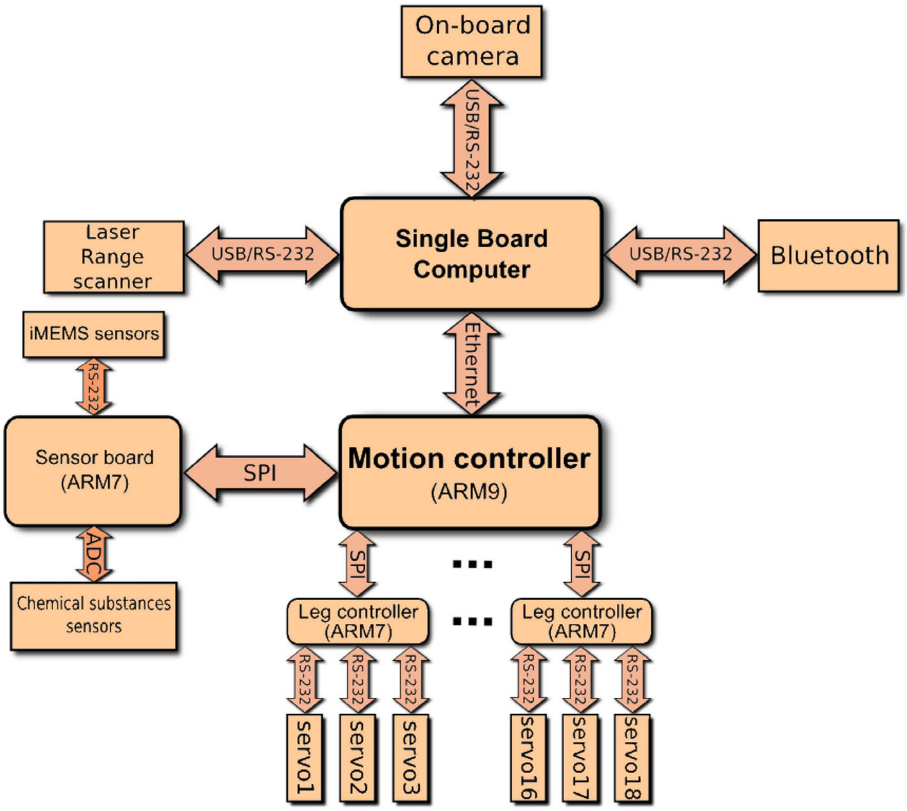

Fig. 5. Control system architecture of the robot.

board, one for each leg to communicate with integrated servomotors and to measure leg state. An additional microcontroller is used to process the measurements of the robot's internal state (inclinometers and gyroscopes) and environment's state (chemical substances sensors).

The robot can also work on batteries. The 7.4V Li-Ion/Polymer Battery Pack Modules are used. It allows to work about 20 min without charging.

4.3. Communication channels

For a distributed control system the most important feature is a fast communication between modules. To achieve a high speed transfer of data between robot modules appropriate communication channels are used. The communication protocol is fitted to the specification of the transferred data and function of the modules. However the highest layer of the control system is not physically connected directly to the measurement unit it can send request through the middle layer of the system and then use obtained data for motion planning. The communication at the top software layer does not depend on physical communication channels.

The robot is equipped with integrated servomotors. The Hitec HMI protocol allows to send reference values of angles in joints, modify the speed of the drive, and to receive information about the servomotors state. It supports one-wire protocol and allows to send orders 300 times per second.

The reference values for the servomotors are computed by the motion controller, and then they are sent to the leg controllers. The communication should be fast to prevent delays between the movement of the first and the last leg. To achieve the minimal delays the fast and bidirectional Serial Peripheral Interface (SPI) is used. The EP9302 microcontroller works as a master SPI while the leg controllers and sensor board work as SPI slave units. The master unit chooses the microcontroller to communicate with. The communication frame reserves single byte for flags, six bytes for data and one byte for checksum. When the communication error occurs the frame is resend. The SPI communication is significantly faster than Hitec HMI protocol. When all the reference values are received by the leg controllers the data are transmitted forward through Hitec HMI protocol simultaneously. Such a method is much more efficient than sending the reference values to the servomotors one by one.

The communication frame also includes the checksum byte. If the communication error occurs the data frame is retransmitted. The communication delays are significantly smaller than a mechanical reaction of the drives. The retransmission, if it happens, does not cause the delays in motion control.

The communication between the top layer of the control system and the motion controller is based on the TCP/IP protocol. Such a communication is easy to implement because both the top and the middle layer of the control system are embedded on the computers with Linux operating system on-board. Various tasks of the first two layers are performed by different software modules. The communication between modules which are located on the same computer unit is also based on the TCP/IP protocol. It makes the communication simpler. There is the same standard for exchanging data between modules on the same computer and between two separated devices.

The maximal frequency of the modification of desired value for servomotor is 333Hz. The proposed architecture of the control systems allows to modify the state of each leg 111 times a second. It is possible because of the simultaneous work of the leg controllers and the use of the SPI protocol to communicate between low layers.

5. Application software

The application software of the robot is divided into a number of separate and independent modules. It allows to create a flexible control application software for the robot and enables programming of each functionality separately by different programmers. Each module can be easily replaced and modified without any changes in other modules. Only the application programming interface should be predetermined. Such an architecture allows to develop the software independently and simultaneously. The scheme of the application software is shown in Fig. 6.

The software for the ARM7 processor is written in C and is interrupts driven. The controller is waiting for the orders from the top layer of the control system. When the request from the higher layer is obtained, the reference values are sent to the appropriate servomotor or the information on sensor's state is returned. Most of the values mea-

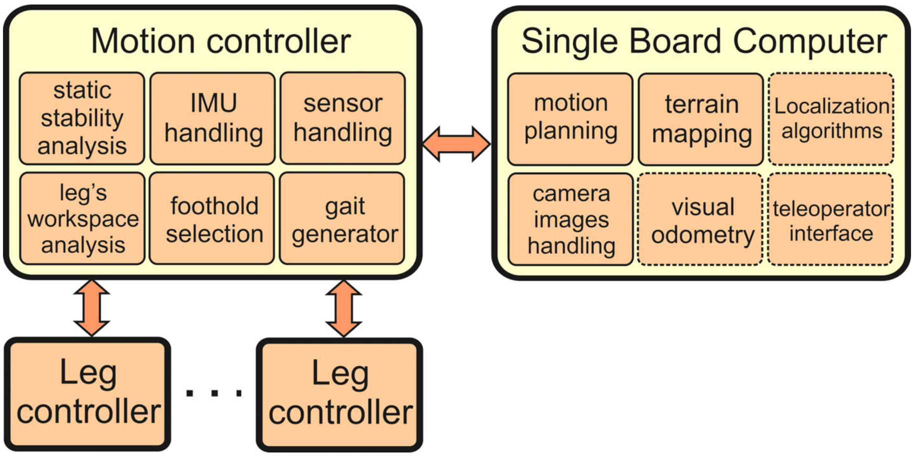

Fig. 6. Modules of the application software.

sured by sensors are cyclically stored. It allows to filter a noisy measurement on the leg controller and to send filtered values to the middle layer.

The main task for the software of the motion controller is to generate the movement of the robot. There are several modules which generate platform movement and allow to walk by using any type of gait [1]. The modules which address safety aspects of the movement execution are also situated on the middle layer. These modules check the static stability of the robot and prevent from setting the positions of the feet which are located outside the robot leg's workspace. While walking on the rough terrain there is also a module for the appropriate foothold selection [2]. It can be used with structure light sensor which measures the shape of the terrain in front of the robot [4]. Another module measures the orientation of the robot by using accelerometers and gyroscopes.

The top layer of the control system, which is placed on the single board computer, is dedicated to motion planning, mapping, machine vision and image processing algorithms. There is a separate module on the single board computer for planning the movement and sending appropriate orders to motion controller. Another module is dedicated to map building. It collects measurement data from the laser range finder and creates a map of the surrounding terrain [18]. There is also a module which manages the camera resources and images. A space for self-localization, visual odometry and teleoperation modules is also available. These modules are under development.

6. Conclusions

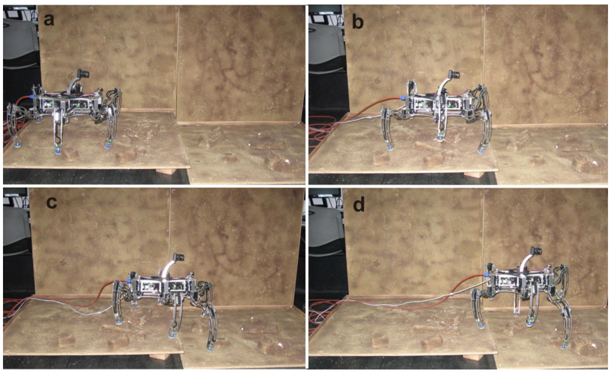

Fig. 7. The robot while walking on rough terrain.

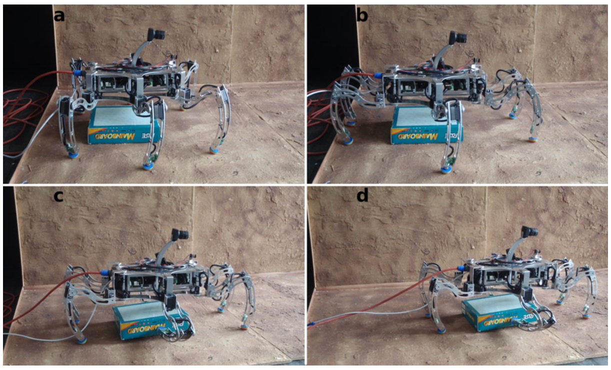

Fig. 8. The robot while quadruped walking.

The presented robot is prepared to operate in an urban environment. The typical obstacles in such an environment are stairs, curbstones or unstructured debris. The mechanical structure, control system and application software are developed to make the robot available to deal with such obstacles.

To support the walk on the unstructured terrain the robot uses a laser range finder and the module for mapping [17]. The data are also used for planning the movement of the feet and for the selecting appropriate footholds [2], [4]. The robot uses contact sensors to assure appropriate support for its legs. The motion controller executes the movement orders to reach a desired position. Fig. 7 documents an experiment on the rough terrain. Due to its mechanical structure the robot is also able to walk on four legs while carrying a load. The documentation of this experiment is shown in Fig. 8. The capabilities of the Messor robot could be seen in the movie available at http://lrm.cie.put.poznan.pl/JAMRIS2010KWDB.avi.

The Messor robot requires further development. In the near future the robot will be able to climb stairs. An appropriate algorithm is currently tested on the robot. Moreover further improvement in the environment sensing and path planning is needed.

ACKNOWLEDGMENTS

This work is funded by MNiSW grant N514 294635 in years 2008-2010. Dominik Belter is a scholarship holder within the project “Scholarship support for PH.D. students specializing in majors strategic for Wielkopolska's development”, Sub-measure 8.2.2 Human Capital Operational Programme, co-financed by European Union under the European Social Fund.

AUTHORS

Krzysztof Walas* - Institute of Control and Information Engineering, Poznan University of Technology, ul. Piotrowo 3A, Poznan, Wielkopolska, Poland. E-mail: Krzysztof.Walas@put.poznan.pl.
Dominik Belter - Institute of Control and Information Engineering, Poznan University of Technology, ul. Piotrowo 3A, Poznan, Wielkopolska, Poland. E-mail: Dominik.Belter@put.poznan.pl.
* Corresponding author

References

[1] D. Belter, Parametrized gait generation system for hexapod walking robot, *Zeszyty Naukowe Politechniki Warszawskiej. Problemy robotyki*, K. Tchoń, C. Zieliński (Ed.), vol. 2, 2008, pp. 565-574. (in Polish)

[2] D. Belter, “Adaptive Foothold selection for Hexapod Robot Walking on Rough Terrain”. In: *7th Workshop on Advanced Control and Diagnosis 2009*, Zielona Góra, Poland, CD-ROM, 2009.

[3] D. Belter, K. Walas, A. Kasiński, “Distributed control system of dc servomotors for six legged walking robot”. In: *Proceedings of Int. Power Electronics and Motion Control Conference*, Poznan, Poland, 2008, pp. 1044-1049.

[4] D. Belter, P. Łabecki, P. Skrzypczyński, “Map-based Adaptive Foothold Planning for Unstructured Terrain

Walking". In: *IEEE Int. Conference on Robotics and Automation*, 3rd-8th May 2010, Anchorage, Alaska, USA, pp. 5256-5261.

[5] D. Belter, P. Skrzypczyński, "Rough Terrain Mapping and Classification for Foothold Selection in a Walking Robot". In: *IEEE Int. Workshop on Safety, Security & Rescue Robotics*, 2010.

[6] C. Borst, M. Fischer, S. Haidacher, H. Liu, G. Hirzinger, DLR Hand II, "Experiments and Experiences with an Anthropomorphic Hand". In: *IEEE Int. Conference on Robotics and Automation*, Taipei, Taiwan, vol. 1, 2003, pp. 702-707.

[7] B. Gassmann, K.-U. Scholl, K. Berns, "Locomotion of LAURON III in rough terrain". In: *International Conference on Advanced Intelligent Mechatronics*, Como, Italy, 2001, vol. 2, pp. 959-964.

[8] P. Gonzalez de Santos, J.A. Cobanoa, E. Garcia, J. Estremera M.A. Armada, "A six-legged robot-based system for humanitarian demining missions", *Mechatronics*, vol. 17, 2007, pp. 417-430.

[9] M. Gorner, T. Wimbock, A. Baumann, M. Fuchs, T. Bahls, M. Grebenstein, C. Borst, J. Butterfass, G. Hirzinger, "The DLR-Crawler: A testbed for actively compliant hexapod walking based on the fingers of DLR-Hand II". In: *International Conference on Intelligent Robots and Systems*, Nice, France, 2008, pp. 1525-1531.

[10] B. Klaassen, R. Linnemann, D. Spenneberg, F. Kirchner, "Biomimetic Walking Robot Scorpion: Control and Modeling", *Robotics and Autonomous Systems*, vol. 41, 2002, pp. 69-76.

[11] J.Z. Kolter, M.P. Rodgers, A.Y. Ng, "A control architecture for quadruped locomotion over rough terrain". In: *Proc. IEEE Int. Conf. on Robotics and Automation*, Pasadena, USA, 2008, pp. 811-818.

[12] J.Z. Kolter, M.P. Rodgers, A.Y. Ng, "Stereo Vision and Terrain Modeling for Quadruped Robots". In: *Proc. IEEE Int. Conf. on Robotics and Automation*, Kobe, Japan, 2009, pp. 1557-1564.

[13] E. Krotkov, J. Bares, T. Kanade, T. Mitchell, R. Simmons, W.L. Whittaker, "Ambler: a six-legged planetary rover". In: *5th International Conference on Advanced Robotics, Robots in Unstructured Environments*, 19th-22nd June 1991, Pisa, Italy, pp. 717-722.

[14] Y. Okubo, C. Ye, J. Borenstein, "Characterization of the Hokuyo URG-04LX Laser Rangefinder for mobile Robot Obstacle Negotiation*", SPIE Conf. Unmanned Robotic and Layered Systems*, Orlando, USA, 2009.

[15] H. Qing-Jiu, N. Kenzo, "Humanitarian mine detecting six-legged walking robot and hybrid neuro walking control with position/force control", *Mechatronics*, vol. 13, 2003, pp. 773-790.

[16] K. Walas, D. Belter, A. Kasinski, "Control and environment sensing system for a six-legged robot", *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 2(3), 2008, pp. 26-31.

[17] P. Łabęcki, D. Rosiński, P. Skrzypczyński, "Terrain Perception and Mapping in a Walking Robot with a Compact 2D Laser Scanner". In: *Emerging Trends in Mobile Robotics* (H. Fujimoto *et al*., ed.), Singapore, World Scientific, 2010, pp. 981-988.

[18] C. Ye, J. Borenstein, "A Novel filter for terrain mapping with laser rangefinders", *IEEE Transaction on Robotics and Automation*, no. 20(5), 2004, pp. 913-921.

[19] A.A. Yumaryanto, J. An, L. Sangyoon, "A Cockroach-Inspired Hexapod Robot Actuated by LIPCA". In: *IEEE Conference on Robotics, Automation and Mechatronics*, Bangkok, Thailand, 2006, pp. 1-6.