CONTROL AND ENVIRONMENT SENSING SYSTEM FOR A SIX-LEGGED ROBOT

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Abstract:

This paper describes the architecture of the six legged robot. Robot kinematics for single leg and for the multi-legged platform is presented. For the control of the robot equipped with a number of sensors a three-layer control system has been designed. It consists of a host computer (in the first, teleoperation layer), of a single master microprocessor on the robot board (second layer) and of six microprocessors each of them for one leg (third layer). The communication between the first and the second layer is performed in duplex mode through the RS232 link via the Bluetooth channel, and between the second and the third control layer through the SPI bus. The robot sensing system consists of rotary potentiometers in each joint, of the leg as well as of a dual-axis accelerometer and gyroscope for platform orientation control. On board camera for remote vision is available.

Keywords: *multi-legged robot, sensors, control system.*

1. Introduction

The main challenge for mobile robots is to improve their mobility in a rough terrain. Wheeled robot is not appropriate for exploring considerably uneven ground. But walking robots can move in such a surrounding because they have the ability to adapt their posture and gait to the variations of the surface relief. An insect like robot mechanical architecture has been chosen as an object of research and development namely a six-legged robot for the reason of its inherent stability, while walking. The described robot is equipped with a number of entero- and exteroceptive sensor systems to support its walk in unknown and unstructured environment, such as:

- frontal camera,
- inclinometric subsystem,
- contact sensors,
- robot joint sensors.

Modular control system based on communicating controllers reflects the allocation of particular control tasks and provides a space for further expansion.

The overall design, implements and practically verifies the idea of a low-cost, ubiquitous robot platform, which is able to carry a number of on board sensors and a camera. The potential tasks for such a robot are sentry, risk assessment, localisation of the source of the pollution, remote monitoring on the uneven ground. There is an interesting perspective of possibility of testing walks and gaits as a function of ground properties - such as its softness, humidity or surface geometry.

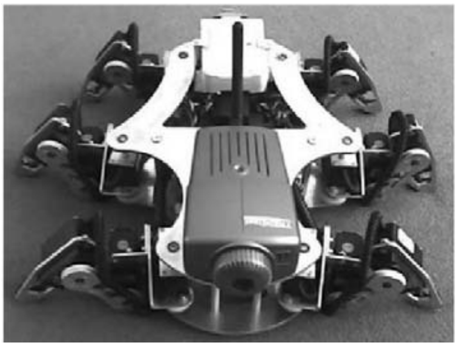

Fig. 1. Robot Ragno.

2. State of the art in walking robots

Several types of walking robots have been described. One of the robot classification principles could be by the number of legs:

- One-legged robots – an example is a 3D One-Leg Hooper [4]. It was built at Massachusetts Institute of Technology. The main advantage of this solution is the absence of leg cooperation problem, which greatly simplifies the robot balance study. Such a robot uses hoops in order to move. It is stabilised dynamically and it is stable only while jumping.
- Two-legged robots – the best example for the robot from this group is ASIMO [5]. It was built and developed at Honda Laboratories – Japan and aimed to mimic the sophisticated human walk. Another humanoid robot has been recently built at Toyota Laboratories [7]. Not only can it walk, but also can play violin or trumpet.
- Four-legged robots – this type of robot resembles a dog or a horse. There are many examples known of this type of machines. One of them is BISAM (Biologically InSpired wAlking Machine). It has legs that mimic horse forelegs and was built in FZI Karlsruhe – Germany [1]. Another example is AIBO – a robodog built at Sony Laboratories – Japan [3]. There is a lot of research activity performed around four-legged robots all over the world. Especially the research is on cooperation and teamwork and AIBO is used in experiments.
- Six-legged robots – robots of this kind has been built in a number of universities all over the world. One of the examples could be LAURON IV from FZI Karlsruhe – Germany [2]. It is a robot aimed to the urban rescue missions. Another example is HEXAPOD V4B, which was built at the Micromagic Systems – UK for commercial purposes [8]. It featured in "Harry Potter" as one of characters. This group of robots resembles insects in their shape and walk.

- Eight-legged robots – a good example is the SCORPION built at the Universität Bremen – Germany [6]. Thanks to its eight legs this robot is capable of walking on different surfaces (heavily dusty or muddy), but it can also climb on bars and pipes. It has a symmetrical mechanical construction, so after turning it upside down, it can still continue its walk.

Each of the above listed mechanical structures has its advantages and some drawbacks. After long deliberation the six-legged variant has been chosen for our purposes. The mechanical structure of such a robot is quite complex but the gait control is easier here than with the one-, two- or even four-legged robots. In case of six legs robots the accounting for the robot dynamics in control is not essential due to the predominantly static stability of such a robot during the walk. The main advantage of a six-legged robot is its augmented adaptability to the terrain relief, due to its kinematic redundancy. It can easily walk on the rough, curved or even locally steep surfaces by adapting its posture to the geometry of the ground contacts. On the other hand, the number of DOF of the robot is kept at the level enabling efficient distributed control.

3. Robot Kinematics

Direct kinematics of the leg

To describe the legs of the robot the Modified Denawitt-Hartenberg convention (MD-H) was used. The attachments of coordinate frames to each link for the left and right leg are shown in Fig. 2.

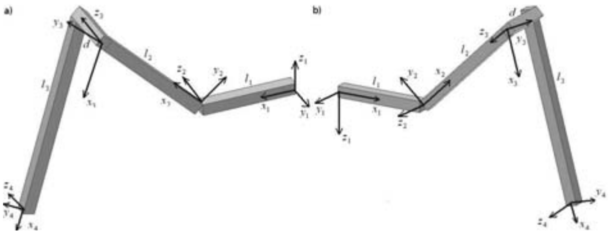

Fig. 2. Frames attachment for: a) right leg, b) left leg.

The legs of the robot are described in Fig. 2 as if the viewer would stand behind the robot looking towards its front.

The legs dimensions are:
- l_1= 0,0323 m – length of link 1,
- l_2= 0,0450 m – length of link 2,
- l_3= 0,0700 m – length of link 3,
- d = 0,0193 m – offset of link 3.

The appropriate MD-H parameters for the right leg are shown in Table 1.

Link	α_{i-1}[rad]	a_{i-1}[m]	$\theta_i=q_i$[rad]	d_i[m]
1	0	0	q_1	0
2	$\pi/2$	l_1	q_2	0
3	0	l_2	q_3	0
4	0	l_3	0	d

For left leg parameters only $\alpha_1=\pi/2$ and $d_4=-d$ are changed.

Inverse kinematics of the leg

To get compact equations for the inverse transform, the geometrical solution is proposed, leading to the result, which can be easily and quickly computed.

- calculating angle θ_1 from (1) (Fig. 3) one obtains:

$$\theta_1 = a\tan 2(y,x) + a\tan 2(d,\sqrt{r^2-d^2}) \tag{1}$$

where $r=\sqrt{x^2+y^2}$

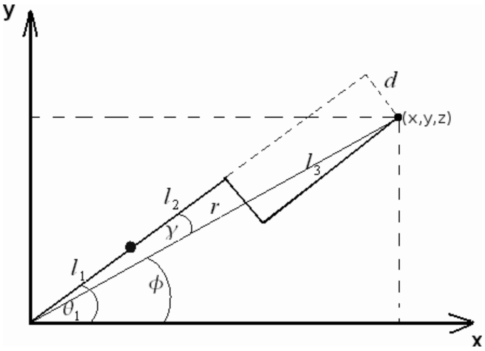

Fig. 3. Calculating angle θ_1.

- calculating θ_3 angle from (2b) (Figure 4) one obtains:

$$\cos(\theta_3) = \frac{c^2-l_2^2-l_3^2}{2\cdot l_2\cdot l_3} \tag{2a}$$

$$\theta_3 = a\tan 2(-\sqrt{1-\cos^2(\theta_3)},\cos(\theta_3)) \tag{2b}$$

where $e=\sqrt{r^2-d^2}$ $\quad c=\sqrt{(e-l_1)^2+z^2}$

- calculating θ_2 angle from (3a) (Figure 4) one obtains:

for the left leg

$$\theta_2 = a\tan 2(z,e-l_1) + a\tan 2(f,g) \tag{3a}$$

where $f=l_3\cdot\sin(-\theta_3)$
$g=l_3\cdot\cos(\theta_3)+l_2$

for the right leg

$$\theta_2 = -a\tan 2(z,e-l_1) + a\tan 2(f,g) \tag{3b}$$

where $f=l_3\cdot\sin(\theta_3)$
$g=l_3\cdot\cos(-\theta_3)+l_2$

The opposite sign of θ_2 angle for the left and the right leg results from the difference in frame assignment for the appropriate leg. All equations were derived with elbow up assumption, and to obtain the equations for the elbow down the sign in equations for θ_3 should be changed.

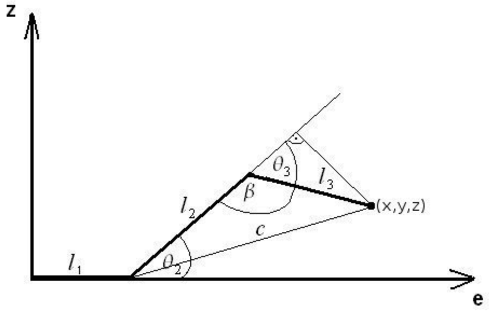

Fig. 4. Angle θ_2 and θ_3 in the robot's leg.

Direct kinematics of the complete robot

In order to find direct kinematics of the robot, both direct and inverse kinematics of the leg has to be used. The legs are attached to the local fixtures frames on the platform of the robot. Such a solution implies the constant values in transformation matrices of particular legs. Assigning the leg frames to the global frame would imply the necessity of building a new frame for a leg every time the robot moves. The local frame assignment on the platform depends only on the geometrical dimensions of the robot corps. This is shown in Fig. 5.

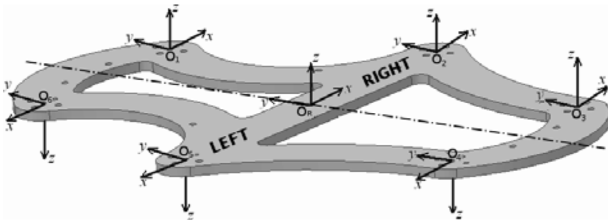

Fig. 5. The local frames assignment to the robot body.

While solving the overall kinematics of the robot it is assumed that the "hip" of the leg is fixed and the tip of the leg is moving. The virtual move of the tip of the leg to the right gives the movement of the hip to the left, so that the platform moves to the left. The overall move of the platform can be computed as a function of foot movement by using kinematics of the whole robot (4).

$$S = O_R \cdot O_i \cdot A_1^i \cdot A_2^i \cdot A_3^i \cdot A_4^i \tag{4}$$

where S – foot position in global coordinates,
O_R – robot position in global coordinates,
O_i – robot platform coordinates frames,
A_j^i – appropriate MD – H matrix,
i – foot number.

4. Robot control system architecture

The logical architecture of the robot control system is shown in Fig. 6.

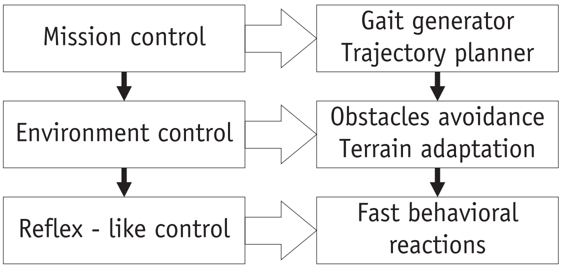

Fig. 6. Robot system control architecture.

A general control task of the robot is decomposed into three hierarchical subtasks. Choosing layered architecture has consequences for its hardware implementation. Usually, each layer has its counterpart in hardware, while various components of the same subtask can be assigned to different hardware layers.

At the top of the architecture scheme are the algorithms responsible for the proper execution of the mission. Trajectory planner and gait generator are the main components at this layer. They are responsible for the estimation of the robot path in global environment, which is a necessary condition for the proper mission accomplishment. After the trajectory has been planned, a suitable gait should be chosen to perform it. The choice depends on the current terrain type. While robot is walking through the flat and smooth terrain it can use tripod gait. But it should switch to the wave gait while the surface is getting more irregular. Parameters of all gait types can be modified appropriately on-line in order to guaranty the proper tracking of the desired path. Gait types can be switched on-line as well as a function of ground quality.

Second layer of control will be responsible for the reactions to obstacles on the robot course. Images from the frontal camera are analysed at the teleoperation workstation to detect the obstacle, its distance and free space enabling the modification of the planned robot path. Moreover, this layer supports the robot to adapt gait and posture to the surface slope (based on inclination sensors). This is important for the stabilisation of the camera orientation, as it eases the remote interpretation of camera images by an operator. Furthermore the stabilisation of the robot platform allows for the use of various walking strategies, while the robot is walking uphill or downhill.

The third layer will be responsible for the simple but fast reactions (reflex-like) to unexpected accidents and events. As it is very important to keep the robot stability while walking. Whenever the robot places its tip on an unexpected obstacle or in the hole, while trying to follow the next command without accounting for such an event, it would probably fall down or stall. To prevent such a faulty behaviour the controller immediately blocks the leg movement once the micro switch on robot's foot tip detects the unexpected obstacle or lack of a base. Control algorithms placed at higher layers of the system are getting informed about this event and thus can make a proper decision about the reaction (possible error recovery). This usually results with changing the gait strategy. Because the algorithms at the lowest layer have a short response-time to such detected events, it is not important how much time the reaction at the higher layer would take, as the robot's balance is preserved mainly due to its inertia.

The proposed robot control system architecture had a great impact on its actual hardware implementation. The implemented robot control hardware system configuration is shown in Fig. 7.

The implementation of the robot control system is split into four physical layers:

1. Host computer (a teleoperation workstation),
2. Master SPI layer (with Atmega128 on board microcomputer),

3. Leg controller (6xATmega8 – slave nodes on SPI),
4. Integrated servo controllers.

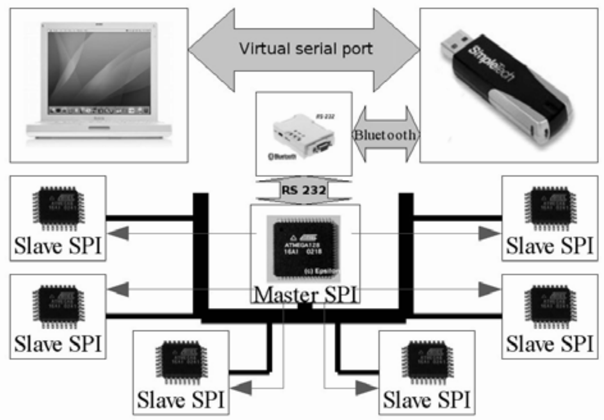

Fig. 7. Robot control hardware system.

First layer dedicated to the mission control is placed on host computer equipped with bluetooth/usb device for the wireless direct robot control. But rich computational resources of the host are used to perform the image processing algorithms on image sequences transmitted from the robot on-board camera with WiFi. Current images from the robot camera are just simply displayed on-line on the host computer screen. This provides visual feedback supporting the teleoperation.

Additionally, at that layer also a special system for remote control support and for monitoring of the robot state was embedded. This application includes the simulator, which visualise to the remote operator a current robot state. This gives a possibility to virtually preliminarily check the results of the next move virtually (predictive display), which makes the mission control easier.

The next two layers are placed on robot platform. Connection between host computer and robot is wireless. The main element of the second layer is an 8-bit processor ATmega128. It is responsible for the communication between the robot and the host. It sends the reference values to leg controllers and acquires data from sensors placed on the robot platform. Such a fast feedback loop allows for the implementation of simple robot reactions to unexpected obstacles. This micro controller interprets orders received from the host computer. If there is a command to set legs positions, the microcontroller simply interprets data in a frame and passes over the appropriate data to the particular leg controllers. It also collects feedback sensors data. Whenever host sends request for the robot state information, ATmega 128 edits a special frame holding the measurements and transmits it to the host.

The third layer consists of six controllers one for each leg. They work as slave nodes on SPI. Whenever they receive reference values for leg's joints they resend it to the integrated servo controllers. All these microprocessors work in parallel and independently. They allow forcing the desired positions of 18 robot joints with small delays. Maximal delay time is equal to 0.85 ms and it is less than the delay of the mechanical drive reaction. Processors within this layer measure joints angles and detect legs contact with the ground by monitoring micro switches, which are mounted on leg's foot.

Finally, the fourth layer consists of HS-645MG servos. They are controlled by using the pulse length signal within the range 0.9 to 2.1 ms with neutral point at 1.5 ms. The refresh rate is equal 50 Hz. Maximal motor torque is about 0.9 Nm.

5. Robot sensory system

To improve robot's performance while walking in the real world, robot is equipped with a number of types of sensors. Each joint of the leg has a potentiometer providing rotation angle feedback. It is used for position control inside the servomotor and provides information on actual angular position of each joint for the kinematic algorithms. Moreover, at the tip of each leg the micro switch is placed to detect its contact with the ground. This feedback allows for detecting obstacles lying on the ground and for adapting the gait to the encountered situation.

On the platform of the robot the dual-axis accelerometer is placed and it is used as a 2 DOF inclinometer. Its feedback signals enable a lateral stabilisation of the platform. The robot is thus able to compensate for the slope of the terrain. The orientation around vertical axis of the robot in the global space is measured by using a gyroscope. The output of this sensor is a current angular velocity. By calculating the integral of the gyroscope signal the cumulative orientation of the robot is obtained. Both the accelerometer and the gyroscope used are miniature MEMS sensors.

The principal exteroceptive sensor fixed to the robot board is a wireless camera. The images are directly sent to the host computer, where the image processing takes place or they can be used directly by human operator. The information extracted from images automatically characterises the surrounding of the robot and can be used in order to support the teleoperation mode.

6. Communication channels

Two independent communication channels are used to remotely control the robot. The architecture of communication channels is shown in Fig. 8.

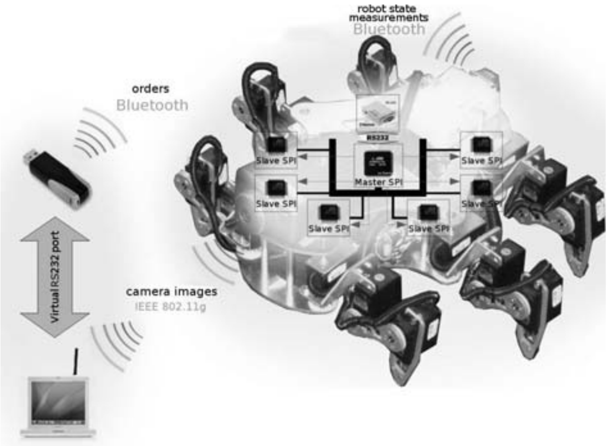

Fig. 8. Robot communication channels.

Camera images are sent wireless by using IEEE 802.11g protocol. In our case this is a broadband unilateral channel. Images are just simply sent to the host computer as a sequence of frames.

Robot movement control is achieved by sending proper reference values to the leg joints. To set the desired robot state the host computer creates an appropriate frame, starting with the proper flag at the beginning. The first bit (a flag) defines order type and specifies the frame length. The frame is shown in Fig. 9. After the flag, computer sends reference values for each servomotor in the given order. To that purpose the Bluetooth channel with USB device working as a virtual RS-232 computer port is used. The frame received by the robot is decomposed into smaller parts, which are sent to the leg controllers.

Communication between micro controllers on the robot board is performed through the SPI protocol. Master SPI processor chooses the controller to communicate with and sends the desired values of joint rotation angles. After interpreting the order, the reference values are sent to appropriate servomotors. Sensor data acquisition is performed periodically also on the robot platform. Master SPI controller collects data from all sensors. SPI interface works in a full duplex mode. When the slave SPI controller receives reference values it sends measurement results to the Master SPI processor at the same time. When host computer wants to get to know the robot state, it sends 1-bit flag. As a response the master SPI controller assemblies an appropriate frame by using collected sensory data and sends it to the host computer by using a Bluetooth protocol device working as the RS-232 bus.

flag	$\alpha 1$	$\beta 1$	$\gamma 1$	…	$\alpha 6$	$\beta 6$	$\gamma 6$

$\alpha i, \beta i, \gamma i$ – reference values for i-leg

$\Theta 1$	$\Phi 1$	$\Psi 1$	…	$\Theta 6$	$\Phi 6$	$\Psi 6$	S1	…	S6	Ax	Ay	G_{tem}	G_{ref}	G_{rot}

$\Theta i, \Phi i, \Psi i$ – i-th leg measured angles
Si – microswitch state on i-th leg
Ax,Ay – accelerometer measurements
G – gyro data (tempeture, Uref and rotation)

Fig. 9. Orders frame and measurements data frame.

7. Application software

All control software on host computer was written in C++. An appropriate library was created. It includes a number of classes used for solving robot kinematics equations and for computing reference values for the leg joints. Special class to communicate with the robot was created as well. It collects data and assemblies the frames that are then properly interpreted by the robot. Using this library requires the creation of the object class CRobot and the use of the special methods, created to implement the appropriate robot control.

Additionally, to make the teleoperations easier, the interface including an animated visualisation of the robot graphical model was built with OpenGL library components. It allows to virtually detect mutual collisions between the robot legs and to anticipate the robot state for choosing in advance the appropriate control algorithm in predictive mode.

8. Implemented gait types

The robot has been programmed to walk with two types of gaits. The first, which was used, is a tripod gait. It is the fastest, statically stable gait for six-legged robots. While walking in this mode, robot has always three legs placed on the ground and its centre of gravity lays inside the support triangle. The support triangle is defined as a connection between contact points of three robot legs.

There is a second gait implemented – the wave gait. Here in each beat, five legs stand on the ground and they move robot platform. Sixth beat completes a single cycle in this mode.

With these two types of gaits the robot can move in any lateral direction. Due to it the robot can walk forward, backward, sideways or slantwise. Using robot kinematics the host computer calculates a control sequence, which allows for the walk along the pre-programmed reference path.

The robot has two modes of control. On the first mode the host computer sends short commands defining only few steps ahead. After the robot changes its position the operator makes decision about the next moves. These sequences repeat until the robot reaches a desired position. This mode makes the teleoperation easier. The robot covers short distances and the operator can change gait type and direction of the movement in a fast reaction for the unexpected obstacles. Disadvantages of this control mode could be the number of gait parameters involved. Operator might have a great difficulty in changing them fast and properly.

The second operation mode give greater autonomy to the robot. In this mode it is necessary only to define robots path in global environment. The host calculates the appropriate control sequence, which leads robot to the end point. While walking robot can use its enteroceptive sensors to change gait type instantly (as the surface inclination changes).

At the moment any special software supporting image analysis is not implemented. The matter of a further development is the use of the camera images analysis onboard, to make robot walking in rough terrain even more flexible, safe and autonomous.

9. Conclusion

The assumed target performance of the design has been achieved. The physical device has reached the following performance measurements:

- throughput of the communication link – 10 direct robot control frames per second,
- energy supply – average current supply required is 6.3 A,
- maximal walking speed – 0.16 m/s while moving forward,
- ability to overcome the vertical obstacle up to 0.08 m high.

Complex, multilayer architecture of the control system has been obtained, allowing keeping the assumed precision requirements and operation in real-time.

Dual robot platform control loops have been checked: the one based on feedback potentiometers and kinematic model and second based on MEMS accelerometers providing direct inclinometry measurements.

Two robots are currently available at the Institute for ongoing research. Future work will be focused on the onboard computer vision system for obstacle detection, visual odometry, and 3D scene reconstruction. Optical flow techniques will be used to manage the single-camera image stream. Laser pointer and/or 3D laser scanner/ range-finder are planned in order to support the vision system.

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