Introduction

Walking robots for the transport of objects, motion over a complex surface, handling with process environment, and performance of various assembly and service operations require the control system design, providing various motion possibilities, manoeuvring, control of displacement and orientation of the robot body (for example, climbing through narrow passes, turns, the orientation of the equipment or tools on the body etc.). A number of the problems devoted to climbing tasks have been shown in publications [4] considering robot movement inside or outside a pipeline. For this task the robot has to press itself against the inner or outer surface of the pipe and to move, so that support reactions were inside cones of friction. In [5] are considered in details the problems of climbing up/down a large obstacle by the walking robot with rigid body. However, the functional capabilities of the walking robot can be essentially expanded by change of the body design. The overcoming of obstacles equal to the geometrical size of the robot are not covered in the literature except the works [1, 2], which simulate the climbing of six-legged robot on a high ledge by means of a change in the body configuration during the separate phases of climbing. In [2] it is shown, that size of the obstacles, which the robot can overcome, increases in case of the body having controlled segments.

Thus the technical purpose of this work was the development of a robot with additional controlled DOF (degrees of freedom) in the body as well as with the possibility of the measurement and control of support reactions (near navigation will be the subject of the future investigations).

Improvements in the robot construction

In accordance with requirements discussed above a multilegged robot with articulated body “SLAIR2” (Fig. 1) has been developed at the Fraunhofer Institute for Factory Operation, Magdeburg, Germany and Otto-von-Guericke University of Magdeburg, Germany. The robot mechanics, sensor system and control system make it possible to maintain the additional flexibility in the body, to measure and control the support reactions as well as to control and forecast the robot motion stability.

Mechanics

The robot construction consists of \( n = 3 \) modular segments (shoulders) linked to each other through two DOF joints and 6 legs. Each shoulder includes one articulated body segment linked with two 3-DOF-insectomorphic legs. It is possible to extend the construction to the case of \( n > 3 \) shoulders. The main mechanical parameters are shown in the Table 1. The robot drives are...
s servomotors, with maximal power $P_{DC} = 4.5\, \text{W}$, with
potentiometer with angular range $\varphi_{POTI} = \pm 90^\circ$ and
gears with ratio $i_{GEAR} = 251$ and efficiency
$\eta_{GEAR} = 85\%$.

2.2 Sensor System
The sensor system of the robot consists of compo-
nents that are standard for mobile robots and that make it
possible to achieve autonomous robot functions in an en-
vironment. It includes:

Table 1. The main mechanical parameters of the robot

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg lengths</td>
<td>$l_E = 300, \text{mm}$</td>
</tr>
<tr>
<td>Thigh length</td>
<td>$l_1 = 120, \text{mm}$</td>
</tr>
<tr>
<td>Shank length</td>
<td>$l_2 = 180, \text{mm}$</td>
</tr>
<tr>
<td>Total body length</td>
<td>$l_B = 660, \text{mm}$</td>
</tr>
<tr>
<td>Segment length</td>
<td>$l_{RS} = 220, \text{mm}$</td>
</tr>
<tr>
<td>Total robot mass</td>
<td>$m_{\text{ROBOT}} = 3.2, \text{kg}$</td>
</tr>
<tr>
<td>Maximal speed</td>
<td>$v_{\text{ROBOT, MAX}} \approx 1, \text{km/h}$</td>
</tr>
<tr>
<td>Max power consumption</td>
<td>$P_{\text{MAX}} \approx 90, \text{W}$</td>
</tr>
</tbody>
</table>

- 22 potentiometers and 22 current sensors (installed in each
  robot joint),
- 6 three-component force sensors (mounted in each
  leg’s Shank),
- 2-axis gyroscopic sensor (located in body), and
- further it will be equipped with near navigation sen-
  sor system (stereoscopic camera or laser-scanner).

In accordance with the requirements on measurement
and control of the support reactions, the developed force
sensor consists of two parts: the core measuring lateral
components of support reaction, and the elastic parallelo-
gram module for measurement of the longitudinal com-
ponent. The sensor is designed for loadings up to $F_{CONTACT} = 50\, \text{N}$; interference between channels does not exceed 1%.

2.3 Control System
The hierarchically organized modular control system
(Fig. 2a, 2b, 2c) consists of two parts PC-side and robot-
side. PC-side realizes the interaction with user and pro-
duces the control signal for robot joints as well as moni-
tors all actuators and sensors of the robot. Robot-side, realized by fast and flexible DSP, includes the hardware
abstraction layer (HAL) for drive and sensors as well as
joint position controllers. The real-time connection be-
tween two parts is made via RS-232 and can be extended
to USB, FireWire®, WLAN or Bluetooth®. All this pro-
vides flexibility and simplifies the development of control
algorithms. The control system can also be extended for
the additional shoulders in exactly the same manner as the
mechanical structure.

3 Climbing
The climbing tasks include all previous investigated
basic locomotion tasks (special attention to prediction and
the control of motion stability) and require additionally
the estimation of the friction cones between feet and bear-
ing surface, changes in the gait in gallop during a large
slope, as well as active control of the additional DOFs in
the robot body.

3.1 Friction cone definition
The solving of this task is connected with the deter-
mination of the Coulomb friction coefficient $k$ between
feet and ground and can be carried out similar to estima-
tion of the ground mechanical properties. That means the
robot apply the load in normal and tangential direction to
the ground and fix the maximum load level where the foot
begins moving. The corresponding relation
$k = \max\left(\frac{F_{\text{TANGENTIAL}}}{F_{\text{NORMAL}}}\right)$ is the desired value of
the Coulomb friction. This value also is nonlinear and
depends on applied $F_{\text{NORMAL}}$.

3.2 Climbing the obstacles with smooth slope
The next control algorithm for climbing the obstacles
with smooth slope does not need the switch to the sym-
metrical gallop gait and has the following main idea: the
robot body must follow the large irregularities of the
ground (bigger than standard adaptation zone in the gen-
eration of the step cycle) considering the algorithm
(Fig. 3):
Firstly, the sensor system for near navigation (or an operator in our case) detects the imaginary radius of corner and determines normal to the calculated surface taking into consideration the robot clearance.

Than concerning the determined normal the robot body segments must be controlled according to the given formula:

\[
\phi_{\text{REF}} = \phi_{\text{NEXT \_SEGMENT}} - \phi_{\text{PREVIOUS \_SEGMENT}}.
\]

The more and smaller body segments the robot has, the smoother it can follow the bearing surface and the smaller deviations from the calculated support surface (cycle) are. Real deviations will be eliminated by adaptive step cycle generation unit (adaptation zone) and reactive gait controller (transition to support phase only with contact).

### 3.3 Climbing the obstacles with big slope

Only the vertical obstacles equal in height to the robots body length can be overcome. In the case of obstacles with a big slope, the preliminary switch to the “symmetrical gallop” gait is important. The start configuration of the robot must guarantee that the robot longitudinal axis is in the same plane as the normal to the overcoming obstacle surface. The main control idea remains the same.

Fig. 4 shows a comparison of climbing between robots with rigid (left) and flexi (right) body. As can be seen, the articulated body allows for a closer approach of the COM to the ledge. The articulated body also makes it possible to adjust the angle \( \alpha \) between the body segment and horizon better and therefore to overcome bigger obstacles.

\[
h_{\text{MAX \_FLEXY}} = 300 + 220 \cdot \sin(80^\circ) = 516 \, \text{mm}.
\]

The usage of articulated body brings significant advantages concerning to calculation of the required maximal motor torque. In the most critical case for a drive (support on the middle and front shoulders and lift up the back shoulder legs) the maximal motor torque \( \tau_{\text{MAX}} \sim l_B \cdot \cos(\alpha) \) is inversely proportional to cosine of angle \( \alpha \).

**Reference**

The new construction and a supervisor control system for the movement of a six-legged walking robot are presented. In this paper it is shown that by using articulated body, the multi-legged robot becomes possible to solve a large number of improved locomotion tasks including such task as climbing. Simulation of various classes of movements of legs and body of the developed system has confirmed advantages of the developed construction and algorithms.

multi-legged robot, articulated body, hierarchical control system, climbing