Walking Robot with Force Controlled Legs and Articulated Body

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In this paper it is shown that by using force information and articulated body, the multi-legged robot becomes possible to solve a large number of simple and improved locomotion tasks. Force control is needed to increase the adaptability of the legged robot to irregular terrain and to distribute the foot forces during locomotion over rigid and soft soil. The algorithms based on the information about the vectors of main force acting on the robot feet have been developed and the experimental results are presented.

1 Introduction

Today, many questions about multilegged walking robots (the choice of construction, the design of control system, as well as locomotion organization) are known and well investigated. These investigations consider usually multilegged robot locomotion on smooth or easy rough terrain mainly on hard ground (indoors applications), overcoming small obstacles, body maneuvering etc. From the algorithmically point of view this class of operations can be realized on robot kinematical level by means of periodic gaits and contact information in discrete form (yes/no). From the mechatronical point of view this class of operations can realize robots with rigid bodies and sensors of the “inner information” (joint velocity/position, motor current, and gyroscope). Even foot contact can be organized with the aid of current sensors.

Recently investigations of improved robot tasks are concerned with the multilegged robot locomotion over an impassable road or a strongly complex terrain such as earthquake affected area, mountain regions, high ledges, ditches, trenches. The key performance for such tasks is the additional body maneuvering [6,7], the measurement and control of support reactions [3,4,5] as well as the control and forecasting of the robot motion stability as well as the availability of information about obstacles [1,2,3]. From the mechatronical point of view it is connected with enhancements in the robot construction, with using the sensors of the “outer information” (interaction force, near navigation). From the algorithmically point of view it is connected with the software development for the adaptive interaction with environment, for the robot stability control, for the free gait (not mentioned in this article), and for the climbing tasks.

A number of the problems devoted to climbing tasks have been shown in publications [4,5] 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 [1] 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 [6,7], which simulate the climbing of six-legged robot with an articulated body on a high ledge by means of a change in the body configuration during the separate phases of
climbing. In [7] 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). The algorithmically purpose of this work is the development of control algorithms for the desired mechanical interaction with environment, for the robot motion stability, and for the overcoming the large obstacles.

2 Improvements in the robot construction

In accordance with requirements discussed above a multilegged robot with articulated body “SLAIR” (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 one DOF joints and 6 legs. Each shoulder includes one articulated body segment linked with two 3-DOF-insectomorphomorphic 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 servomotors, with maximal power \( P_{DC} = 4.5W \), with potentiometer with angular range \( \varphi_{POTI} = \pm 90^\circ \) and gears with ratio \( i_{GEAR} = 251 \) and efficiency \( \eta_{GEAR} = 85\% \).

![Figure 1: Modular multilegged robot “SLAIR” with articulated body.](image)

Table 1. The main mechanical parameters of the robot.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>leg lengths</td>
<td>total ( l_{LEG} = 314mm )</td>
</tr>
<tr>
<td></td>
<td>shoulder ( l_s = 64mm )</td>
</tr>
<tr>
<td></td>
<td>thigh ( l_t = 100mm )</td>
</tr>
<tr>
<td></td>
<td>shank ( l_z = 150mm )</td>
</tr>
<tr>
<td>body dimensions</td>
<td>total length ( l_b = 760mm )</td>
</tr>
<tr>
<td></td>
<td>segment length ( l_{BS} = 260mm )</td>
</tr>
<tr>
<td>total robot mass</td>
<td>( m_{ROBOT} = 3.2kg )</td>
</tr>
<tr>
<td>maximal speed</td>
<td>( v_{ROBOT_{MAX}} = 1km/h )</td>
</tr>
<tr>
<td>effective load</td>
<td>( m_{LOAD_{MAX}} = 2kg )</td>
</tr>
<tr>
<td>max power consumption</td>
<td>( P_{MAX} = 90W )</td>
</tr>
</tbody>
</table>

Sensor system

The sensor system of the robot consists of components that are standard for mobile robots and that make it possible to achieve autonomous robot functions in an environment. It includes:

- 20 potentiometers and 20 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 sensor system (stereoscopic camera or laser-scanner).
In accordance with the requirements on measurement and control of the support reactions, the developed force sensor (Fig.2) consists of two parts: the core measuring lateral components of support reaction, and the elastic parallelogram module for measurement of the longitudinal component. The sensor is designed for loadings up to $F_{\text{CONTACT}} = 50N$; interference between channels does not exceed 1%. The spherical form of foot provides good friction with a support along all directions of interaction and is preferable considering absence of a gimbal-joint between leg and foot.

### Control system

The hierarchically organized modular control system (Fig.3a,3b,3c) allows the realization of the locomotion as well as manipulation tasks and consists of two parts, PC-side and robot-side. PC-side realizes the interaction with user and produces the control signal for robot joints as well as monitors all actuators and sensors of the robot. The “Action” and “Primitive” levels are located on PC-side and realize the control signal specifying and appropriate leg trajectories generation for both locomotion and manipulation tasks. PC-side realizes additionally the interaction with user. The “Servo Level” is located on-board and controls and monitors 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 between two parts is made via RS-232 and can be extended to USB, FireWire®, WLAN or Bluetooth®. All this provides 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 Extended locomotion tasks

All above-mentioned properties of the mechanical structure, sensor system and control system make the following discussed extended locomotion tasks for the multi-legged robots possible.

- motion over complex terrain with different mechanical ground properties: foot force distribution, estimation of the mechanical ground properties & friction cone, leg compliance control;
- motion stability control;
- climbing the obstacle with smooth and vertical slope.

In contrast to basic locomotion tasks which can be achieved through modification of control parameters on “primitive level” extended locomotion tasks are more complex and must modify additional parameters on the “action level” of the control system using the sensors of “outer information” (interaction force and near navigation).

Task 1: motion over complex terrain with various mechanical properties of the support terrain.

The motion over complex terrain with various mechanical properties of the bearing surface (especially soft ground) differs strongly from the motion on the terrain with hard ground. Firstly, in the absence of force control, the inaccuracies in the robot kinematics, the uncertainties in sensor or control system can lead to significant mechanical loading upon separate legs. Therefore the reactive forces under the feet must be actively distributed and controlled.

Secondly, the explicit control of the calculated distributed support reactions is very complicated and due to uncertainties can led to unwanted effects such as clearance variation. Therefore the additional criteria of the relationship between the foot positions and support reactions, namely the robot compliance, must be fulfilled.

Thirdly, the variation in the mechanical properties of the bearing surface affects the compliance control quality and even can cause instability and oscillation. Therefore the compliance control system is to be adaptive. One way of this adaptation is an estimation of the ground mechanical parameter. Other way is to control behaviour of the coupled system “robot leg – ground”.

Task 1a: foot force distribution.

As the system is statically indeterminate with respect to forces acting on the legs (support can be made with more than three legs), so support reactions change in a random way. The commanded vertical force components are computed from the body orientation relative to the gravity vector, and from the leg configuration. They must satisfy the static equilibrium equations:

\[ \sum_{\text{legs}} F_{\text{VERT}}^{\text{leg}} = P \cdot \sum_{\text{legs}} F_{\text{VERT}}^{\text{xleg}} = P \cdot \sum_{\text{legs}} F_{\text{VERT}}^{\text{zleg}} = P \cdot \sum_{\text{legs}} F_{\text{COM}} \cdot \sum_{\text{legs}} F_{\text{VERT}}^{\text{xleg}} = P \cdot \sum_{\text{legs}} F_{\text{VERT}}^{\text{zleg}} \]

where \( P \) is the robot weight, \( x^{\text{leg}} \), \( z^{\text{leg}} \) are coordinates of the foot. It is clear that if \( n > 3 \), the solution may be chosen ambiguously and the additional criteria must be added. There are different ways of eliminating the indeterminacy. Let us require that the vertical force components should satisfy:

\[ \sum_{\text{legs}} \left( F_{\text{VERTICAL}}^{\text{legs}} \right)^2 \rightarrow \min \cdot \]

This condition has the sense of energy optimization. Thus, the active distribution of support reactions allows for the reduction of loads on the robot structure and of the energy consump-
tion of leg drives (Fig. 4).

![Figure 4: Experimental results of vertical components of food forces in locomotion over rigid surface without and with force distribution algorithm.](image)

**Task 1b: leg compliance control.**

The basic idea of the robot compliance control consists in a force sensitive interaction between the robot and the environment. A quantitative measure of the compliance control shows the impedance or admittance of the robot system. For the walking robot, the impedance of the closed system “leg-ground” plays the more important role. The desired impedance of the leg is represented by equation:

\[ Z_{\text{ref}}(s) = \frac{F_{\text{env}}(s)}{X_{\text{ref}}(s)} = M_{\text{ref}} s^2 + D_{\text{ref}} s + S_{\text{ref}}, \]

with \( M_{\text{ref}}, \ D_{\text{ref}}, \ S_{\text{ref}} \) - task defined Inertia, Damping and Stiffness matrix.

Generally, there are some problems (Fig. 5) in the compliance control of the closed system “separate leg–ground”, because of: interconnection between the legs; under determined system (not controlled DOFs - degrees of freedoms - in the robot due to mobility characteristics); system with unknown variables: often undefined environment, variable load.

The way to overcome mentioned problems is making the system adaptive. There are two main methods of adaptation: parameters and signals adaptation. The parameters adaptation estimates the mechanical parameter of the ground and than optimises the basic impedance controller. The signals adaptation controls the reference position correction due to make equal the interconnected “robot-ground” behaviour to desired impedance.

**Task 1b: leg compliance control with estimation of the ground mechanical properties.**

The impedance control algorithm is based on the standard indirect or self-tuned adaptive controller (Fig. 6). For correct and robust parameter identification the appropriate model of the mechanical part of the ground must be chosen. That model is additionally dependent on the robot weight, foot geometrical parameters and the ground elastic properties (adhesion forces). Sup-

![Figure 5: Compliance control problems.](image)

![Figure 6: Self-tuned impedance controller.](image)
posed that there are no moments of force and only reactions appear at supporting point, two commonly used models can be presented.

The first model considers the elastic properties of the ground:

\[ F_{\text{ENV}} = S_{\text{ENV}} \cdot (r_0 - r) - D_{\text{ENV}} \cdot l \cdot \dot{r}, \ l \geq 0, \]

where \( F_{\text{ENV}} \) is reaction at the supporting point, \( l = (r_0 - r) \cdot n \) is the penetration depth of the foot under the supporting surface, \( r \) is the radius vector of the foot real position, \( r_0 \) gives a point of the foot contact with supporting surface, \( n \) is inner normal unit vector to the supporting surface at a point of a foot contact, \( S_{\text{ENV}} \) and \( D_{\text{ENV}} \) are ground elastic and viscous friction coefficients (stiffness and damping).

The second model is more intended for the real soil with irreversible plastic deformation. The pressure under robot foot can be evaluated by:

\[ F_{\text{ENV}} = k(l/l_0)^{\mu}, \]

where \( k \) and \( \mu \) are the empirical coefficients, the value \( l_0 = \text{lcm} \). Coefficient \( k \) is defined by \( k = k_a/r + k_f \), where \( k_a \) and \( k_f \) are values corresponding to adhesion and internal friction in the ground, and \( r \) is the foot radius. By means of these equations, the permissible pressures under robot legs i.e. permissible load of the robot on the corresponding ground can be evaluated. By investigations, the bearing possibilities of the ground can be determined by resistance of ground medium to shear and pressure. The corresponding “load/penetration depth” relation can be experimentally evaluated with the leg of walking robot equipped with joint angle sensors and force sensors.

This method has one essential lack. Mechanical properties of the ground under one leg can be certain only in that case if the rest part of the robot remains motionless, that is other legs remain motionless on the ground. Such method sharply reduces the speed of the movement on the ground with various mechanical properties.

**Task 1b: leg compliance control with model reference adaptive impedance controller.**

The other solution is connected with optimization of robot leg motion under the condition of getting into contact with a ground. The main goal is “the behaviour of the coupled system ‘robot leg–ground’ should be equal to desirable impedance at any ground mechanical properties”. This condition leads to high quality contact (minimal tendency to oscillations, contact stability, and contact force limitation).

The developed impedance control algorithm is based on the indirect model reference adaptive controller (iMRAC) with feed-forward neural networks as controller and as coupled system identifier (Fig.7) and operates the closed system so its behaviour asymptotically comes nearer to desirable impedance.

**Task 2: stable motion of robot with disturbances.**

If the walking robot is not subject to external disturbances and the mass distribution in the robot is a-priori known, then the definition of the robot COM (centre of mass) needs only additional determination of the robot orientation relative to bearing surface and can be found according the following formulas:
\[
\begin{align*}
\text{COM}_x &= \text{rot} \left( \frac{\sum X_{\text{body}} \cdot M_{\text{body}} \cdot g + \sum X_{\text{leg}} \cdot M_{\text{leg}} \cdot g}{\sum M_{\text{body}} \cdot g + \sum M_{\text{leg}} \cdot g} \right) \\
\text{COM}_z &= \text{rot} \left( \frac{\sum Z_{\text{body}} \cdot M_{\text{body}} \cdot g + \sum Z_{\text{leg}} \cdot M_{\text{leg}} \cdot g}{\sum M_{\text{body}} \cdot g + \sum M_{\text{leg}} \cdot g} \right)
\end{align*}
\]

If the walking robot is a subject of the external disturbances or the mass distribution in the robot is a-priori unknown, then the definition of the robot COM (Center of Mass) is calculated according to:

\[
\begin{align*}
\text{COM}_x &= \text{rot} \left( \frac{\sum X_{\text{leg}} \cdot F_{\text{vertical}}}{\sum F_{\text{vertical}}} \right) \\
\text{COM}_z &= \text{rot} \left( \frac{\sum Z_{\text{leg}} \cdot F_{\text{vertical}}}{\sum F_{\text{vertical}}} \right)
\end{align*}
\]

and needs additionally the measurement of vertical component of the support reaction. Because of contact irregularities this method is not robust and must be extended with additional stabilizing routines.

In order to guaranty stable robot motion, the COM must be forecasted for the next step cycle phases. The most critical is the transition between the step cycle phase (especially from support to rising phase) by the symmetrical gallop gait. The vector correction \( \Delta \text{corr} \) (Fig. 8) scaled in accordance to the desired criteria is used to control the robot stability.

**Task 3: climbing.**

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

**Task 3a: friction cone definition.**

The solving of this task is connected with the determination of the Coulomb friction coefficient \( k \) between feet and ground and can be carried out similar to estimation 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 \( k = \max(F_{\text{tangential}}) / F_{\text{normal}} \) is the desired value of the Coulomb friction. This value also is nonlinear and depends on applied \( F_{\text{normal}} \).

**Task 3b: climbing the obstacles with smooth slope.**

The next control algorithm for climbing the obstacles with smooth slope does not need the switch to the symmetrical 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 generation of the step cycle) concerning the algorithm (Fig. 9):

- Firstly, the sensor system for near navigation (or an operator in our case) detects the imaginary radius of corner and determinate 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:
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).

**Task 3c: climbing the obstacles with vertical slope.**

Only the vertical obstacles equal in height to the robot 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. 10 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.

The maximal overcoming obstacle height can be estimated as following $h_{\text{MAX}} = l_{\text{LEG}} + l_{\text{BODY SEGMENT}} \cdot \sin(\alpha)$. If the body segment length is smaller than the leg length, the usage of articulated body doesn’t yield significant advantages concerning to obstacle height. In our case

$$h_{\text{MAX, RIGID}} = 314 + 260 \cdot \sin(50^\circ) = 497\, \text{mm},$$

$$h_{\text{MAX, FLEXY}} = 314 + 260 \cdot \sin(80^\circ) = 560\, \text{mm}.$$

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 $\tau_{\text{MAX}} \sim l_{\text{RS}} \cdot \cos(\alpha)$ is inversely proportional to cosine of angle $\alpha$.

**4 Conclusions**

Therefore we can conclude the following:

- The multilegged robot with articulated body has been developed. The modular design of the robot and of the control system allows easily to extend and to upgrade the robot with additional capabilities.
• The sensor system makes possible the completion of the basic and extended autonomous tasks in complex environment.
• The robot is specially intended for development of control algorithms, for the investigation of the robot motion over extremely complex terrain, as well as for climbing obstacles that are equal to robot’s body dimensions.

References