Control System of Six Legged Autonomous Intelligent Robot

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Abstract — A new construction and a hierarchical control system of a six-legged walking robot are presented. In this paper it is shown that by using articulated body, the multilegged robot is able to solve a large number of improved locomotion tasks. The new hierarchical control system allows fast-and-easy improvements of the different parts of the control system independently of each other. Simulations and experiments of various classes of movements of legs and body of the developed system have confirmed the advantages of the developed construction and algorithms.

I. INTRODUCTION

Walking robots for transport of objects, motion over a complex surface, handling tasks in process environment, and performance of various assembly and service operations require a control system design, providing different motion possibilities, maneuvering, control of displacement and orientation of the robot body (for example, climbing through narrow passes, turns, orientation of equipments or tools on the body etc.). In the past, research on multilegged walking robots (the choice of construction, the design of control system, as well as locomotion organization) has been in the focus of many working groups. These investigations consider usually multilegged robot locomotion on smooth or slightly rough terrain mainly on hard ground (indoors applications), overcoming small obstacles, body maneuvering etc. From the algorithmical point of view this class of operations can be realized at the kinematical level of the robot by means of periodic gaits and contact information in discrete form (yes/no). From the mechatronical point of view it is connected with enhancements in the robot construction, with using sensors of “outer information” (interaction force, near navigation). From the algorithmical point of view it is connected with software development for the adaptive interaction with environment, for the robot stability control and for the free gait (not mentioned in this article).

Thus the technical purpose of this work is 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 future investigations). The algorithmical purpose of this work is the development of control algorithms for the desired mechanical interaction with environment.

II. IMPROVEMENTS IN THE ROBOT CONSTRUCTION

In accordance with the requirements discussed above a multilegged robot with articulated body “SLAIR2” – Six Legged Autonomous Intelligent Robot version 2 (Fig. 1) – has been developed at the Otto-von-Guericke University of Magdeburg, Germany. The robot mechanics, sensor system and control system guaranty an additional flexibility in the body, to measure and control the support reactions as well as to control and forecast the robot motion stability.

A. 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 \( n \geq 3 \) shoulders. The main mechanical parameters are shown in Table I. The robot drives are servomotors, with maximal power \( P_{DC} = 5.0 \) W, with potentiometer with angular range \( \varphi_{POTI} = \pm 170^\circ \) and gears with ratio \( i_{GEAR} = 244 \) and efficiency \( \eta_{GEAR} \approx 70\% \). It should be pointed out, that the new construction of the shoulder’s differential joint (Fig. 2) brings the double rotation moment on the two rotation axis and realizes the required two degrees of freedom in the
shoulder.

B. 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:

- 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 sensor 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 parallelogram module for measurement of the longitudinal component. The sensor is designed for loadings up to $F_{\text{CONTACT}} = 50 \text{ N}$; interference between channels does not exceed 1%.

### III. CONTROL SYSTEM

The hierarchically organized modular control system (Fig. 3) consists of two parts: PC-side and robot-side. The PC-side system realizes the interaction with user and produces the control signal for robot joints and monitors all actuators and sensors of the robot. The Robot-side system, realized by a 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-485. 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.

#### A. Action level

This level represents the level of references (Fig. 4):

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE MAIN MECHANICAL PARAMETERS OF THE ROBOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>leg lengths</td>
<td>total: $l_{\text{LEG}} = 300 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>thigh: $l_1 = 120 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>shank: $l_2 = 180 \text{ mm}$</td>
</tr>
<tr>
<td>body dimensions</td>
<td>total length: $l_B = 660 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>segment length: $l_{\text{BS}} = 220 \text{ mm}$</td>
</tr>
<tr>
<td>total robot mass</td>
<td>$m_{\text{ROBOT}} = 3.20 \text{ kg}$</td>
</tr>
<tr>
<td>max power consumption</td>
<td>$P_{\text{MAX}} = 90 \text{ W}$</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Modular multilegged robot “SLAIR2” with articulated body.

**Fig. 2.** Construction of the shoulder’s differential joint.

**Fig. 3.** The hierarchically organized robot control system.
references for locomotion tasks and references for manipulation tasks. In this level, such parameters as parameters for step circle (translation speed of robot, type of gait, height of adaptation zone and the whole length of the step circle), course parameters (direction of the robot motion), parameters for robot impedance and etc. are defined for locomotion tasks. The parameters for manipulation tasks, such as the parameters of body translation and rotation as well as parameters specified tool impedance are defined in this level too.

B. Primitive level

The primitive level (Fig. 5) ensures a regular walking pattern in accordance with parameters which comes from the action level. This level can be divided in four parts:

1) Step cycle generation

This part provides the gait generator [4], which is adapted automatically to small irregularities of the supporting surface. As it can be seen on Fig. 6, the gait generator for each leg is adapted automatically to the irregularities of the supporting surface taking into account only the information from the contact sensors and is irrespective of the other legs (cycles). This level is responsible for the formation of the basic support polygon, for it rotation and etc.

2) Compliance control

The basic idea of the robot compliance control [5], [6] 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

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**Fig. 4.** The hierarchically organized robot control system: action level.

**Fig. 5.** The hierarchically organized robot control system: Primitive level.

**Fig. 6.** The adaptive step cycle generation.
the closed system “leg-ground” plays the more important role. The desired impedance of the leg is represented by equation:

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

with \(M_{\text{ref}}, \ D_{\text{ref}}, \ S_{\text{ref}}\) – task defined inertia, damping and stiffness matrix.

Generally, there are some problems in compliance control of the closed system “separate leg-ground”, because of: interconnection between the legs; under-determined system (not controlled DOF’s 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: signals and parameters adaptation.

The first one controls the reference position correction to make equal the interconnected “robot-ground” behaviour to desired impedance. The second one estimates the mechanical parameter of the bearing surface and than optimises the basic impedance controller.

3) COM stabilization

If the walking robot is subjected to the external disturbances or mass distribution in the robot is a-priori unknown, then the definition of the robot COM (Center of Mass) is calculated according to [5], [6]:

\[
\begin{align*}
\text{COM}_X &= \text{rot} \sum X_{\text{LEG}} \cdot F_{\text{VERTICAL}} + \sum F_{\text{VERTICAL}}, \\
\text{COM}_Z &= \text{rot} \sum Z_{\text{LEG}} \cdot F_{\text{VERTICAL}} + \sum F_{\text{VERTICAL}},
\end{align*}
\]

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. 7) scaled in accordance to the desired criteria [5], [6] is used to control the robot stability.

4) Force and position feedback

This part transfers the feedback signals from the lower level (servo level) to the upper level (primitive level) and makes the necessary transformation of them.

C. Servo level

This level (Fig. 8) is located on the robot side and realized in the DSP. Its assignments are the realization of the communication routine, position control of servo DC drives, sensor signals sampling. The whole control process is sampled with the sample time of \(T_{\text{sample}} = 1\) ms.

Position control of servo DC drives is shown in Fig. 9. For the position loop an IPD controller is utilized. The PD part of the controller is realized in the form:

\[
K_p \left( \frac{T(s) + 1(T_s + 1)}{(T_s + 1)(T_s + 1)} \right).
\]

The bode diagram of the open-loop control system is shown in Fig. 10. Simulation and experimental results of the position controlled DC motors of one of legs, during the robot movements, are shown in Fig. 11 and Fig. 12 accordingly. As it can be seen from these two figures, the results of simulation and the results of real experiments are practically identical. The maximal position error is less than 5 grads in the dynamic and be absent (except noise of signal) in the static mode.

IV. CONCLUSION

From the obtained research results the following conclusions can be drawn:

1) The modular design of the robot and of the control system allows easily the extension of the robot construction and the upgrading of the robot with additional functions.

2) The applied sensor system makes possible the completion of standard and advanced autonomous tasks in complex environment.

REFERENCES


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Fig. 10. Bode diagram of the open-loop position control system.
Fig. 11. Simulation results of the position control of DC motors by robot movement with tripod gait.

Fig. 12. Experiment results of the position control of DC motors by robot movement with tripod gait.