Adaptive Impedance Control of Legged Robot

F. Palis\(^1\), V. Rusin\(^2\)

\(^1\)University of Magdeburg, Institute for Electrical Power Systems
Magdeburg, 39106 Germany

\(^2\)Phone (+49) 391 4090853 Fax (+49) 391 4090250 E-Mail: rusin@iff.fraunhofer.de

Abstract - This paper presents an efficient compliance control scheme for legs of walking machines interacting with an uncertain environment and proposes an impact control based on neural system. The proposed method combines the technique of the indirect MRAC (Model Reference Adaptive Control) with the properties of self-learning neural nets. Present research is focused on the optimization of motion of mechanical systems with constraints on the contact with the environment in order to cover given contact quality requirements (minimal tendency to oscillations, contact force limitation, contact stability).

I. INTRODUCTION.

A. Difficulties in control of legged robots

The problem of leg compliance control during the impact and during the interaction between the robot and the environment is one of the central problems in locomotion of legged robots. Legs of walking robots represent a mechanism with variable structure. Its parts form open and closed kinematics circuits in various step phases. Depending on the step phase the control problem involves dealing with both varying dynamics and changes in the control structure. During the transfer phase the controller has to cope only with the dynamics of the leg. In the support phase the controller must take into consideration the dynamics of the body and the interaction with the environment, too. Here, besides the requirements to be met by the speed and/or position control system, additional criterions for the quality of the contact must be fulfilled.

In contrast to industrial manipulators, that are rigidly fixed in space and witch centre of coordinate system has no degrees of freedom, the walking robots have the body-fixed coordinate system, i.e. an additional non-controlled DOF in centre of coordinate system. It means that ground sinking under the robot leg can not be precisely measured. Hence, the a-priori unknown mechanical properties of the ground can not be unique identified using only position and force sensors of robot leg. As a result the leg compliance control system can not be constructed in accordance with classical methods.

Thus, during the construction of the control systems for the walking robot in contact with environment the following essential difficulties must be taken into the consideration:
- The system is under determined, namely there is no special actuator presented, which control the body centre relative to the fixed world coordinate system;
- The system is interconnected, namely there is a coupling interaction effect between the legs through the rigid body of the walking robot;
- The system deals with unknown variables, namely the properties of lifting surface in the general case are unknown and the load can change.

Accordingly, the adaptive controller must be devised.

B. Aim of the work

From problems discussed above escapes the basic goal of the legged robot control in the contact with the environment, namely the construction of such adaptive impedance controller, which ensures the identical behavior of the coupled system “Leg-Environment” as a reaction to the applied external force or external load without any a-priori information about environment properties. This provides the maintaining the horizontal position of the robot body during different sinking of the robot legs into the ground.

C. Impedance control structure

To this aim impedance control method was chosen for the motion control of the leg [7]. Analysis of existing systems and publications [1-6, 8-9] shows that in most cases, control structure can be reduced to a general structure with an inner speed/position control loop which is overlaid by an impedance/force control system (Fig.1). This general

![Fig. 1. Common impedance control scheme](image-url)
structure is widely used and is taken as basis for the presented paper. It has the following advantages:
- providing a generalized approach to impedance and position control of the leg;
- continuous transition from free to constrained motion;
- possibility of the control in Cartesian coordinates.

The basic idea of impedance control consists in the realization of a force sensitive interaction between the robot and the environment with position control. The notion of impedance is common in electrical and mechanical engineering to optimize mechanically coupled electromechanical systems. It is obvious that for realizing impedance control, force reaction must be measured and controlled in a closed loop system. To this aim, legs must be equipped with force sensors.

II. RESEARCH OBJECT AND ITS PHYSICAL MODELLING

As test object, the six legged robot "Katharina" (Fig.2) developed in the Fraunhofer Institute for Factory Operation and Automation IFF Magdeburg, was used. “Katharina” is a high-complex, non-linear, time-variant, electromechanical system and controller design must take into consideration the following non-linearities:
- Mechanical non-linearities: mechanical constraints, changing weight, dry/viscous friction, load variation, non-deterministic and changing environment;
- Electromechanical and electrical non-linearities: variable drive parameters, current and voltage limitation of the converter, discontinuous current mode, noises, sampling time of the control system.

The aim of this work consists in proving the capacity of the proposed impedance control system by simulation. A basic precondition for this is the availability of sufficiently accurate models for the coupled system "drive-robot leg-environment".

To this aim the coupled system that usually is non-linear and time-invariant is simplified and represented as an equivalent mechanical and electrical scheme (Fig.3).

Here, the following parameters are chosen:
- \( M_{1\text{leg}}, M_{2\text{leg}} \) - equivalent masses of the leg system,
- \( C_{\text{leg}}, C_{\text{env}} \) - compliance of the leg and the environment,
- \( D_{\text{leg}}, D_{\text{env}} \) - damping capacity of the leg and the environment,
- \( x_{\text{leg}}, x_{\text{env}} \) - joint position and end position of the leg referred to a fix point,
- \( F_{g1}, F_{g2} \) - weight forces of the leg caused by the equivalent two-mass system,
- \( F_{\text{leg}} \) - force applied to the leg joint by the motor.

For the electric equivalent scheme the well known analogies between electrical and mechanical quantities are chosen. So inductances correspond to masses, resistances to vicious friction and capacities to stiffness. Furthermore it must be stated that the parameters \( C_{\text{leg}}, D_{\text{leg}}, C_{\text{env}}, D_{\text{env}} \) are non-linear and depend on the leg configuration and the interaction force. So the represented equivalent schemes can be considered only as second order linearised model of the real electromechanical system.

III. SELF-LEARNING IMPEDANCE CONTROLLER

A. Control structure

The proposed self-learning impedance controller combines the technique of the indirect MRAC (model reference adaptive control) [10] with the properties of self-learning
neural nets [12, 13]. The utilized control structure (Fig.4) consists of three main components: a basic internal position control loop, a reference model realizing desired system impedance and an external neural impedance controller. For the walking robot the reference model represents the desired impedance of the leg in form of the following equation:

\[
Z_{ref}(s) = \frac{F_{env}(s)}{X_{ref}(s)} = M_{ref}s^2 + D_{ref}s + K_{ref}, \tag{1}
\]

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

Here the neural controller is an impedance controller which modifies the impedance parameters according to the actual support force reactions to guarantee the desired impedance behavior of the system.

The working mechanism of the proposed control system is generally characterized by the following procedure:

- First an external disturbance force \(F_{extern}\) is applied to the plant and the resulting position correction (output of the untrained neural impedance controller) is calculated.
- The desired impedance behavior is formulated as relationship between the applied external force and the desired position change (compliance). This characteristic is shaped as reference model.
- Then, via backpropagation of the error (e.g., square error) the neural impedance controller is trained in order to obtain a minimum error value.
- The whole procedure is repeated for every sample time, so that online adaptation is possible.

Changes in the coefficients of the impedance controller are directly proportional to the deviation of the measured force from the desired behaviour (Fig.5). Thus, on the rigid surface the force deviation will be too great and respectively the impedance gain will be increased. Hence, the robot foot becomes more compliant.

**B. Learning methods**

Investigations have shown that the MLP (multi layer perceptron) with NARX (Nonlinear AutoRegressive with eXogenous input) structure (Fig.6) is the most appropriate net structure for the neuronal model as well as for the neuronal controller. In accordance to this the following notation is used:

**Predictor:**

\[
y(k) = \hat{y}(u(k), \Theta) \quad \tag{2}
\]

**Regressor:**

\[
y(k) = [u(k)\ldots u(k+N_x-N_y), y(k-1)\ldots y(k+N_x-N_y)]
\tag{3}
\]

with

- \(\Theta\) - vector of weight coefficients,
- \(g\) - direct plant dynamics to be realized by the net,
- \(u, y\) - input and output vector,
- \(N_x, N_y\) - number of delayed inputs and outputs.

![Fig. 4. Common addaptive impedance control scheme.](image-url)

![Fig. 5. a) desire force dynamics; b) force response on rigid ground; c) force response on soft ground.](image-url)
As learning procedure for the selected neural nets the gradient descent method “backpropagation” with neuro-biological plausible “Weight Decay”-modification [12] is used which applies a “penalty" to big weights according to (4). The advantage of smaller weights consists first of all in a better generalization property of the network. In addition, they reduce the influence of the initialization of the weight factors.

\[ X_t = X_{t-1} - \lambda_t \cdot R_t^{-1} \cdot \nabla E(X_t) - \eta \cdot dX_{t-1} , \quad (4) \]

with

- \( E(X_t) \) - goodness criterion of the training,
- \( \nabla E(X_t) \) - estimated value of the gradients,
- \( R_t^{-1} \) - direction-correcting matrix,
- \( X_t \) - net coefficients,
- \( \lambda_t \) - step width,
- \( \eta \) - penalty factor.

The following calculation methods of the direction-correcting matrix \( R_t^{-1} \) are examined: KG-method (conjugate gradient); LM-method (Levenberg-Marquard); Quasi-Newton methods: DFP-calculation (Davidon/Fletcher/Powel) & BFGF-calculation (Broyden/Fletcher/Gold-farb/Shanno). The comparison of the learning methods gives evidence of a high approximation quality to all selected learning methods, although the Levenberg-Marquard supplies a learning procedure with a better relation "convergence speed/computing costs" and is generally accepted as a basis-learning procedure.

IV. SIMULATION RESULTS

For the purpose of simulation the robot was represent as two-legged structure, where the legs were interconnected through the rigid body according to (Fig.7.a). The mechanical properties of the ground were represented as widely used stiffness-damping model with different parameters under each leg: \( C_{env1} = 20000[N/m] \), \( D_{env1} = 10[N \cdot s/m] \), and \( C_{env2} = 5000[N/m] \), \( D_{env2} = 100[N \cdot s/m] \). But these mechanical ground parameters were a-priori unknown for impedance controller. Picture (Fig.7.b) shows the work of the proposed impedance controller. First there is the phase of impact and then the phase of interaction between the robot legs and the environment. After the impact the legs are extra loaded, but the desired behaviour remains.

V. CONCLUSION

- Application of the suggested controller is suitable to guarantee a desired impedance of the robot leg by impact and interaction with environment.
- The proposed control structure requires measurement of the output force. Desired impedance behavior is obtained by a neural impedance controller. Its training is based on the error between then real plant output and the reference model output.
- The chosen learning procedures prove high convergence speed and can be realized in real time mode.
- The presented approach is general and can be used for a great variety of technical applications.
The focus of future works will be laid on the combination of the self-learning capacity of neural nets with the possibility of utilization of a priori information. So faster training processes can be guarantied.

REFERENCES