WALKING ROBOT "ANTON": DESIGN, SIMULATION, EXPERIMENTS

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This work presents a new improved six legged mobile robot "ANTON". Its mechanical structure, sensor system and control system are discussed in details. The hierarchically and modular build control algorithms are presented. The Software-in-the-Loop and Rapid Control Prototyping frameworks, which are used by robot development, are presented. An industrial Ethernet-based real-time communication protocol is introduced and the communication ability between the robot-side hardware and PC-side control system is investigated.

1. Introduction

This work presents the actual state of the work in the robotic area of RobotsLab group. RobotsLab group is the team of the young researchers created in cooperation work between the Virtual Engineering department in Fraunhofer IFF and the institute of Electrical Power Systems of OvG-University Magdeburg. The scientific interests of our group lie in the area of robotic, especially in such fields as intelligent and adaptive motion control, optimization and adaption of the mechanic and electronic construction of the complex mechanisms with a lot of degrees of freedoms, planning of complex robots tasks and motion trajectory and so on. In the last 7 years the numbers of legged robots (see Figure 1) were developed. Their mechanical structure and control system were improved. These improvements touch such question as the mechanical construction and the locomotion control system as well as the embedded control system.

Recently investigations of improved robot tasks are concerned with 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 high body maneuvering, the measurement and control of support reactions, the control and forecasting of the robot motion stability as well as the availability of information about obstacles. 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, cameras). 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).

Figure 1. Developed robots constructions in the period 2003-2007 year (SLAIR1, SLAIR2 and ANTON).

The control system of the full or part of autonomous legged robot is almost controlled by embedded system. Commonly the embedded systems are designed to control complex plants such as engines, satellites, vehicles, spacecrafts, and of course CLAWAR. They generally require a high level of complexity within the embedded system to manage the complexity of the plant under control.

Development and test of complex real-time embedded systems consists of many steps from modeling and simulation of the plant till the implementation of the source code in the real hardware. Hybrid techniques, that are used increasingly, are the Software-in-the-Loop (SiL) and the Rapid Control Prototyping (RCP). In our work we use these methods within the development and testing process of six-legged robot.

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, as well as development of such control system that allows simple and rapid development of the complex control algorithms. The algorithmical purpose of this work is the development of control algorithms for the desired mechanical interaction with environment. Moreover the flexible communication bridge for real-time communication between the virtual/real control system and the virtual/real robot is presented as well.

2. Modular six-legged robot "ANTON"

In accordance with the requirements discussed above a multilegged robot with articulated body "ANTON" (see Figure 1, right) has been developed. 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. The real-time communication bridge based on industrial Ethernet protocol EtherCAT was developed. It guarantees the communication between robot onboard electronic and robot control system with sample time 1ms.

The robot construction has three modular segments 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. The robot drives are servomotors, with maximal power 2.8W in knee and 8.68W in other joints. The gear number is 390 in knee and 251 in other joints. 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:

- 24 potentiometers and IGRs (installed in each robot joint),
- 6 three-component force sensors (mounted in each leg's shank),
- 2-axis gyroscopic sensor (located in body) and
- 2 mono cameras in the head of robot.

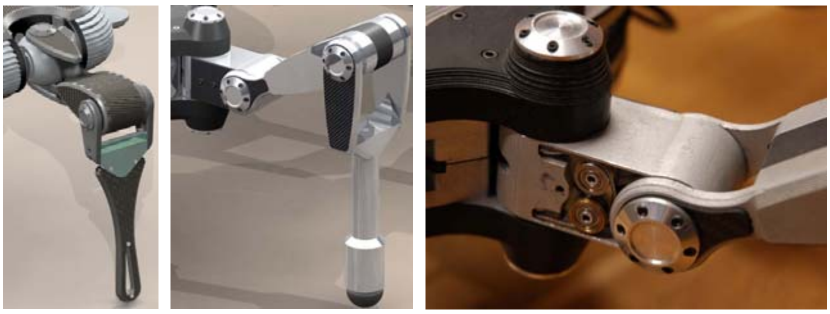

Figure 2. Constructions of legs and the shoulder's differential joints (SLAIR2, ANTON, real differential joint on robot "ANTON").

It should be pointed out, that the 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. The workspace of new differential joint (Fig. 2, center, right) was improved due to the vertical placement of the driving motors and the separation of the rotation axis.

2.1. *Hardware control system.*

Control system with real-time decentralized data gathering and processing builds the kernel of robot system and makes possible development of control algorithms with help of hybrid simulation. The first version of control system has a simple architecture based on DSP and RS485 communication protocol. The next one has been improved and based on WindowsPC-host system with Ethernet communication [4]. The last control system has been already reached the industry level and based on the industry real-time communication EtherCAT. The developed hardware (see Figure 3) consists of NetX communication processor from Hilscher and FPGA.

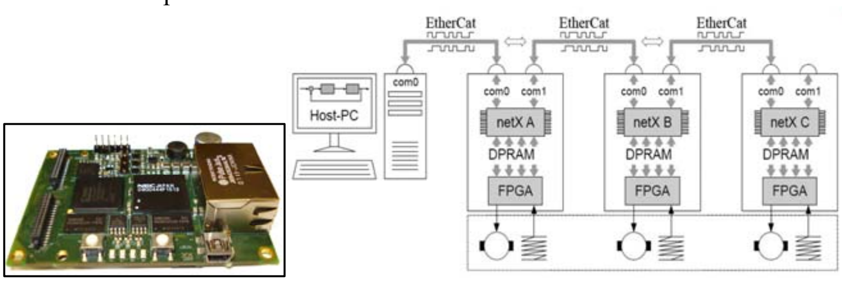

Figure 3. Flexible communication system based on netX processors.

The figure 4 shows the time diagram of communication process. The control system (Control) on Host-PC (xPC Target) is computed each sample time (Tsample) by the information received from the sensors (RD – Receive Data). Computed reference signals of PWM (SD – Send Data) are copied to the EtherCAT packet and the EtherCAT master (CIFx-50) to initialize a telegram (Packet n) transfer. The received data by the EtherCAT slaves (NetX 500) are copied through the DPM (Dual Port Memory) to the FPGA and then to the PWM module.

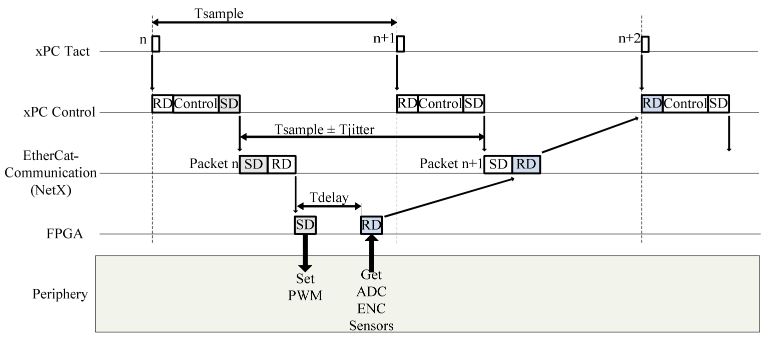

Figure 4. Time diagram of communication process.

The feature of the EtherCAT communication protocol is the exchange of the data in the loop Master-Slave-Master with one solid telegram. Therefore sending of the response information by the EtherCAT slave is required preliminary preparation of the transfer buffer. The delay $T_{delay} = T_{sample}/2$ between the receipt of the telegram by EtherCAT slave and the monitoring of the sensors is realized. This was done for the minimization of the time difference between monitoring of actual sensors information (ADC, ENC and etc.) and the instant of usage them in the control calculation (n+2 xPC Tact). Received information from sensors (RD) is saved to the transfer buffer of the EtherCAT slave. After that it will be sent in the next closest transfer packet (Packet n+1) and will be actual on the n+2 work period.

The standard PC is used as a control computer (Host PC). Therefore the jitter time (Tjitter) in the communication system due to large number of hardware peripheries is occurred. For the minimization of jitter time the practically all of hardware peripheries are tuned off in the BIOS of PC. The maximal jitter time in our communication system is less than $15\mu s$.

Such communication system allows using of important technique in the robotic area as hybrid simulation technique. Starting with the SiL simulation, where the developed control system in Matlab/Simulink has the possibility to communicate with the real legged robot, the control system has acquired a new level so-called Rapid Control Prototyping (see Figure 5).

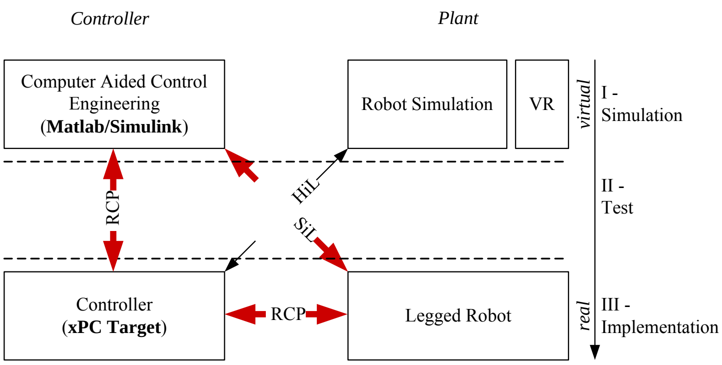

Figure 5. Common scheme of the SiL/RCP structure of the mechatronical system.

2.2. *Software control system.*

The hierarchically organized modular control structure [4] is completely located on PC-side that implements additionally the interaction with user and produces the control signal for robot drives as well as monitors all actuators and sensors of the robot. The robot-side is implemented by fast and flexible FPGA, includes the hardware abstraction layer (HAL) for drive and sensors. The real-time connection between two parts is made via proposed netX® [3] based communication system, described below. 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.

The PC-side hierarchical control system [4] has a three control levels: Action, Primitive and Servo levels. Each of them is for own task responsible. The action level represents the level of references: references for locomotion tasks and references for manipulation tasks. The primitive level ensures a regular walking pattern in accordance with parameters which comes from the action level. This level can be divided in four parts: step cycle generation, compliance control, COM stabilization and force and position feedback. The last level, servo level, is for the realization of the position control of servo DC drives responsible. The whole control process is sampled with the sample time of T_{sample}=1 ms.

3. Experimental results.

This chapter deals with the experimental results during robot movement. Firstly, the position control system is discussed and the experimental results of position control by robot movement are shown. The distributions of the forces during the robot movement are shown at the end of the chapter (see Figure 8 and 9).

Position control of servo DC drives is shown in Fig. 6. For the velocity loop a PI controller is utilized and for the angle loop a P controller is selected.

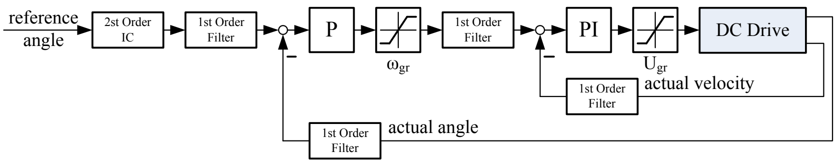

Figure 6. Cascade position control system of servo DC drive.

Experimental results of the position controlled DC motors of one of the legs, during the robot movements, are shown in Fig. 6. 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 is absent in the static mode.

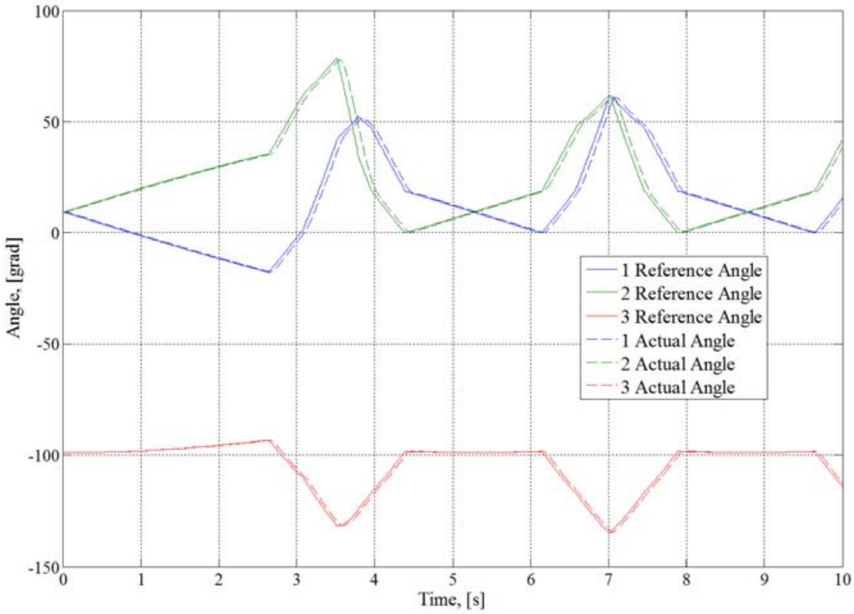

Figure 7. Experimental results of the position control by robot movement with tripod gait.

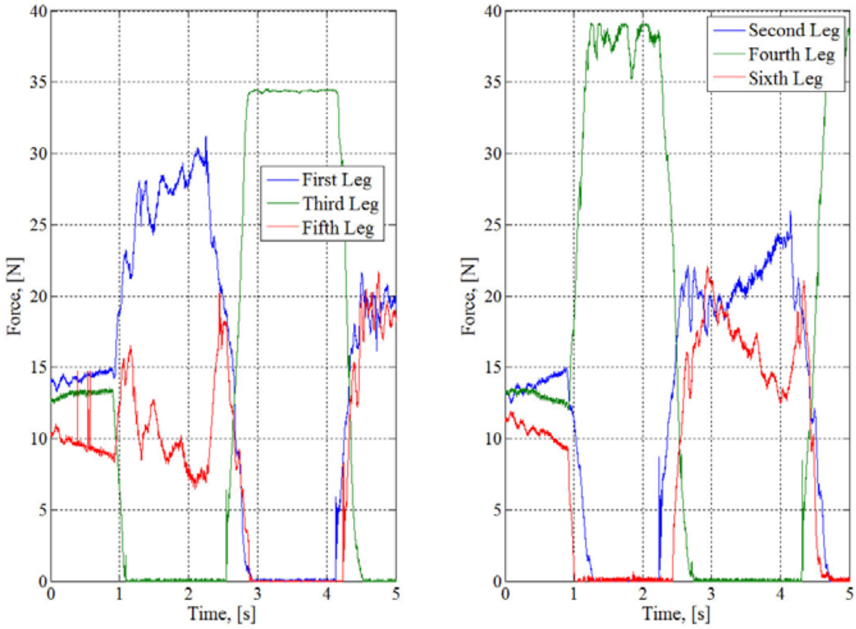

Figure 8. Force distribution by robot movement with tripod gait.

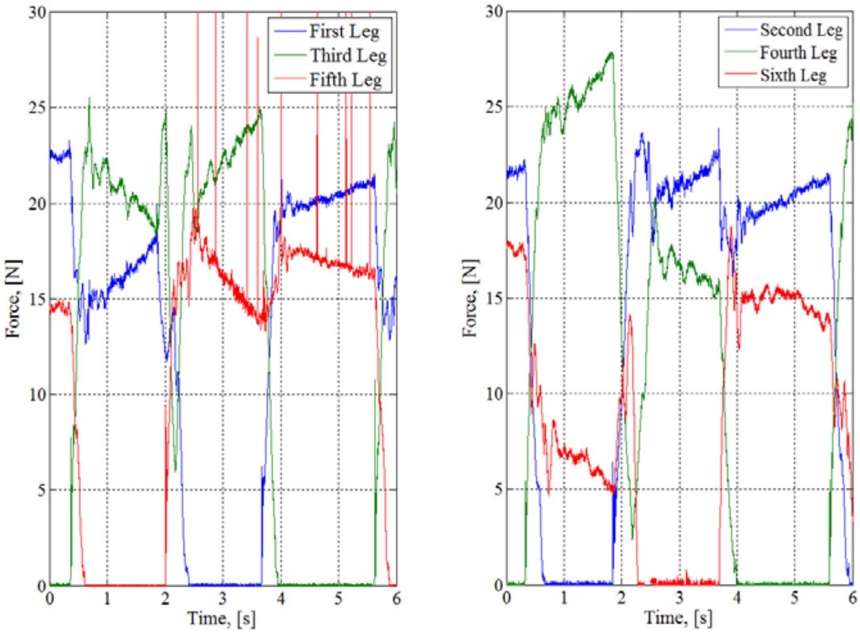

Figure 9. Force distribution by robot movement with gallop gait.

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