Biped Robot "ROTTO": Design, Simulation, Experiments

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The paper deals with designing and developing a biped robot for research purposes. Robot's mechanical structure and drives system are described hereunder in details. Moreover the new modified actuators as well as the possibility to the stabilization of robot with serial elasticity in the joints are discussed. 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

During the last years many researchers are engaged in tasks how to develop the efficient robot prototypes and their control system. The paper deals with designing and developing a biped robot based on experience of the RobotsLab group. Moreover, the control system of fully or partly autonomous biped robot is almost always 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 controlled plant.

Development and test of complex real-time embedded systems require many steps from modeling and simulation of the plant till the implementation of the source code in the real hardware. Nowadays hybrid techniques like Software-in-the-Loop (SiL) and the Rapid Control Prototyping (RCP) are used more and more often. We use these methods while developing and testing the biped robot.

Thus the next technical purpose of this work is to develop a biped robot with the possibility of dynamical walking, as well as to develop a control system that allows simple and rapid development of the complex control algorithms. The purpose of this work is the development of control algorithms for desired mechanical interaction with environment. Moreover, flexible communication bridge for real-time communication between the real control system and real robot is presented.

2 Biped robot "ROTTO"

2.1 Mechanical construction of biped robot "ROTTO"

The main purpose of biped robot constructions is to develop mobile robot able to solve following research tasks:

- research and investigation of low-cost energy gaits (ballistic walking is one of the possible gaits),
- development and research of the methods of force/impedance control of robot foots during contact with the ground,
- investigation of dynamical walking and methods of robot's body stabilization during walking.

To perform above mentioned requirements a biped robot "ROTTO" (see Figures 1 and 2) has been designed and constructed. The kinematical construction of the robot is shown in Figure 2. The robot has been constructed to provide more than 15 Degree Of Freedom (DOF) similar to what human being provides. Suggested robot's construction is characterized by modular structure using linear drive systems in each joint. Bearing structures of the robot are fabricated from carbon material and connected to each other with optimized milled-out aluminum constructions. The aluminum-carbon construction reduces the weight of robot and, at the same time provides sufficient robustness.

The construction of the "hip's" and the "ankle's" joints are implemented in parallel kinematic. Two linear drives actuate the corresponding 2-DOF using the connecting rods and the ball joint. The synchronous and the asynchronous motions of the drives produce the corresponding motion relative to one or another DOF in the joint. It should be pointed out, that such construction ensures the double rotation moment on the two rotation axis.

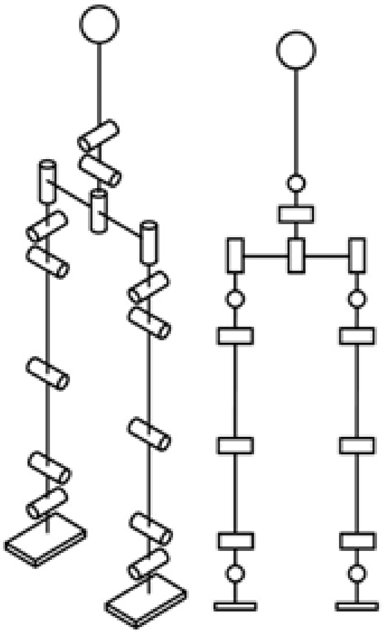

Figure 1 Kinematic structure of biped robot “ROTTO”

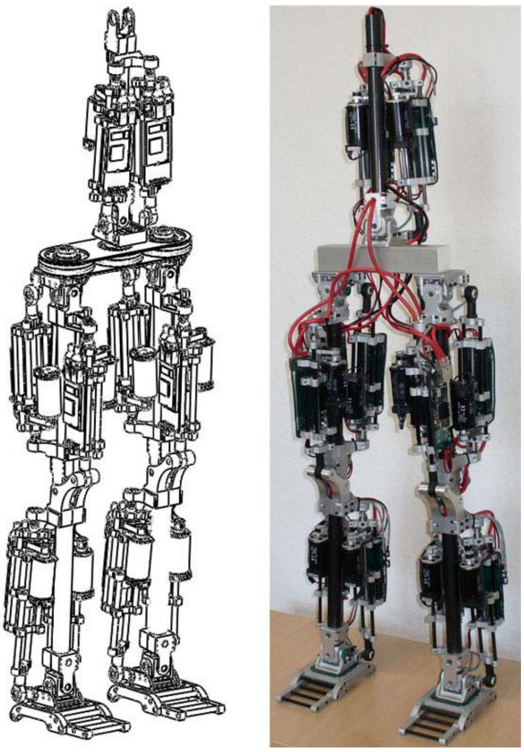

Figure 2 CAD construction (left); real biped robot “ROTTO” (right)

2.2 Actuators of biped robot “ROTTO”

The actuators of the biped robot “ROTTO” are implemented as linear drives (Figure 3). The brushless EC-motor drives the ball screw using belt transmission with a reduction ratio of two. The linear motion of the ball screw’s nut is realized by carbon sticks which are at the same time the direction guide. There is an incremental position sensor on the motor axis. For safety purpose, two limit switches are installed. The on-board electronics collect all the data from sensors and accomplish current control of the EC-motor. The nominal force of this actuator is 128 N with a nominal speed of 0,64 m/s, but the maximal force is 400 N and the maximal velocity is 0,72 m/s. It should be pointed out, that the maximal values of the actuator force and speed can’t be reached at the same time.

The complete integration in one module of the motor, the gear, the sensors and the electronic offers the following advantages:

- reduced volume of actuator;
- better dynamic properties;
- higher power density;
- better efficiency;
- the EC-motor and the modular structure of drive provides better reliability as well as integrated diagnose and observation functionality.

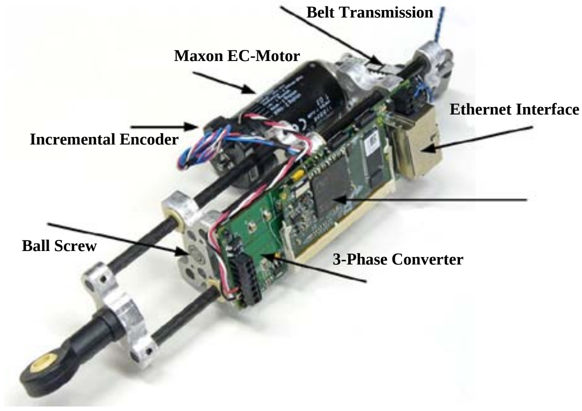

Figure 3 Linear actuator of biped robot “ROTTO”

2.3 Modified actuators of biped robot “ROTTO”

The developed design of the elastic element, combined with the force sensor is shown in Figure 4. Modern composite materials allow a higher energy storage density in the elastic element by smaller masses. The main operating element is a flat coal-plastic spring 5. The deformation of the spring is measured by the Hall-sensor 4 placed in the magnetic field of the two neodymium magnets 3. The glass fibre plate 2 and the screw 1 serve to fix the actor.

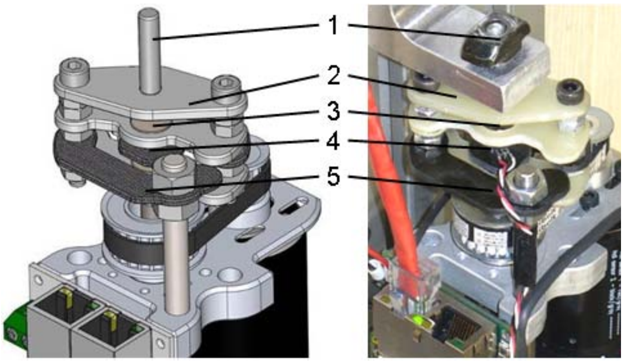

Figure 4 The CAD Model of the elastic actuator (left) and actuator of the robot (right)

2.4 Sensors of biped robot "ROTTO"

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

- absolute magnetic encoder installed in each robot joint;
- incremental position sensor, two current sensors and two limit switches installed in each of the actuator module;
- six-component force sensor mounted in each leg's shank;
- high precision tri-axis inertial sensor installed on the robot body.

Designed foot force sensor provides measurement of forces in wider range in order to comply with the requirements on measurement and control of the support reactions during the dynamical walking. The maximal vertical force is 400N. The maximal values of tangential and lateral forces are chosen up to 300N. The developed sensor is described in [7].

3 Hardware control system

Control system with real-time decentralized data gathering and processing builds the kernel of robot system and allows developing of control algorithms with help of hybrid simulation. The implemented control system is already at industry level and is based on typical real-time communication EtherCAT. The developed hardware (see Figure 5) consists of netX communication processor (Hilscher GmbH). The time diagram of communication process is explained in the [6]. Detailed presentation of decentralize Single-Chip controller based on the netX processor is shown in Figure 6.

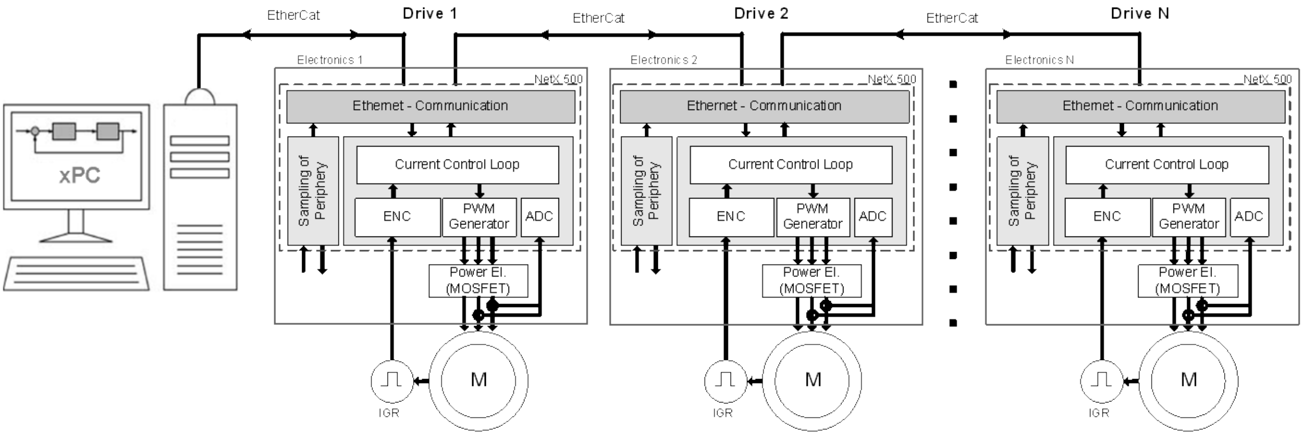

Figure 5 Flexible communication system based on netX processors

The main feature of the EtherCAT communication protocol [5] is the exchange of the data in the loop Master-Slave-Master with one solid telegram. Received information from sensors (RD) is saved to the transfer buffer of the EtherCAT slave. After that it will be sent with 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 the large number of hardware peripheries is occurs. Practically all of hardware peripheries are tuned off in the BIOS of PC to minimize jitter time. The maximal jitter time in our communication system is less than $15\mu s$.

4 Actuator control system

The current control loop is shown in Figure 7. Current control loop is implemented in the netX/xPEC. The current control is calculated synchronously with the PWM module with 28 kHz cycle. The control signal (reference current value) and the sensors signals (motor position, velocity and so on) are exchanged between netX processor and external control PC (with xPC-Target real-time OS) using an EtherCAT communication protocol. Sensors signals are used as the feedback signals for the position/velocity control loops (Figure 8). The sample time of the position/velocity control loops depends on the power of the control PC. In our case (3GHz processor from Intel) the sample time is equal 1ms and can be decrease to 0,5ms.

Phase currents (ia_ist, ib_ist) are measured in the netX by the way of sampling of intern ADC module and are recalculated from coordinate system ABC in coordinate system DQ using Park-Clarke transformation:

$$
\begin{aligned}
i_D &= \frac{3}{2}\left[i_A \sin(\varphi) + i_B \sin\left(\varphi - \frac{2\pi}{3}\right) + i_C \sin\left(\varphi + \frac{2\pi}{3}\right)\right] \\
i_Q &= \frac{3}{2}\left[i_A \cos(\varphi) + i_B \cos\left(\varphi - \frac{2\pi}{3}\right) + i_C \cos\left(\varphi + \frac{2\pi}{3}\right)\right]
\end{aligned} \tag{1}
$$

The error between reference and real current is controlled by the PI controller:

$$
\frac{U}{e_i} = P_{Cont} + I_{Cont} \cdot \frac{1}{1 - z^{-1}} \tag{2}
$$

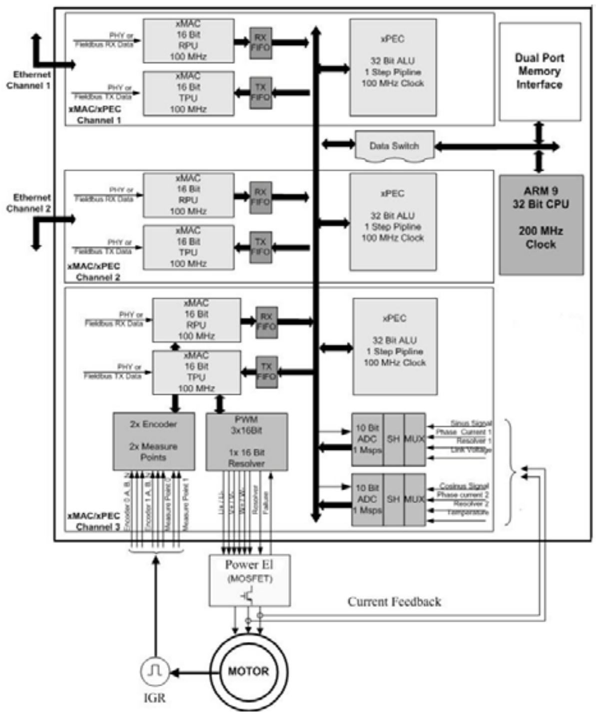

Figure 6 Decentralize Single-Chip controller based on netX processor

The voltage is transformed from the coordinate system DQ in coordinate system ABC using the inverse Clarke-Parke transformation:

$$
\begin{aligned}
U_A &= i_D \sin(\varphi) + i_Q \cos(\varphi) \\
U_B &= i_D \sin\left(\varphi - \frac{2\pi}{3}\right) + i_Q \cos\left(\varphi - \frac{2\pi}{3}\right) \\
i_C &= i_D \sin\left(\varphi + \frac{2\pi}{3}\right) + i_Q \cos\left(\varphi + \frac{2\pi}{3}\right)
\end{aligned}
\qquad (3)
$$

4.1 Velocity/Position control loops

The velocity and position control loops are developed in Matlab/Simulink and are compiled to the control PC using Real-Time-Workshop-Tools [4]. The velocity and the position control loops are shown in the Figure 8.

The accuracy and the correctness of the Permanent Magnet Synchronous Motor (PMSM) control depend on the correct determination of the rotor position. Therefore following algorithm has been developed to determine the exact position of the rotor:

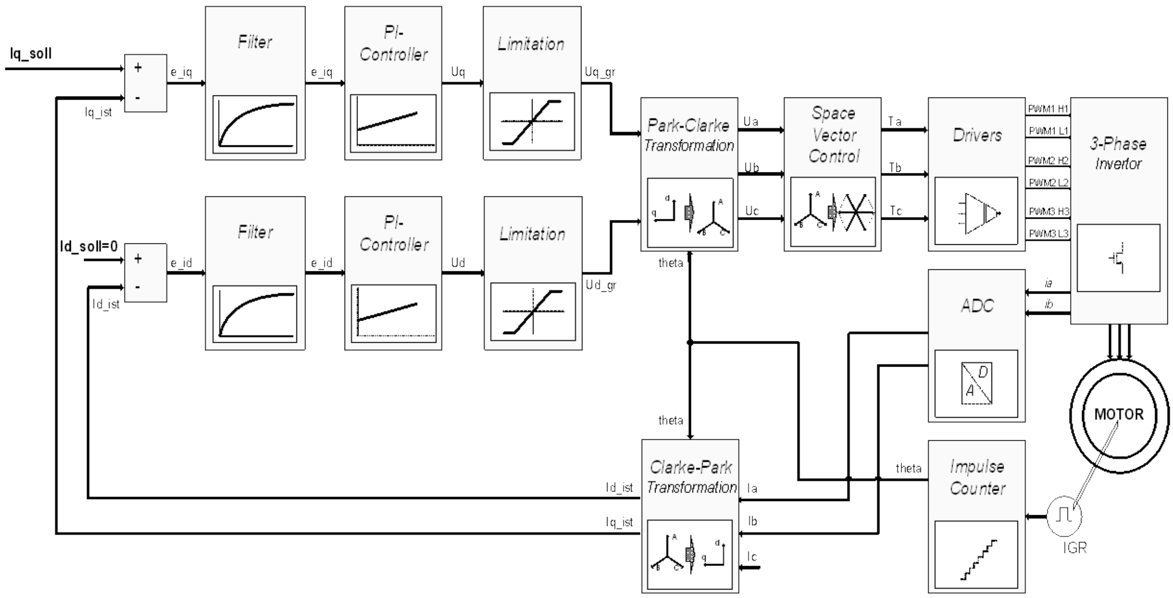

Figure 7 Current control loop in the netX/xPEC

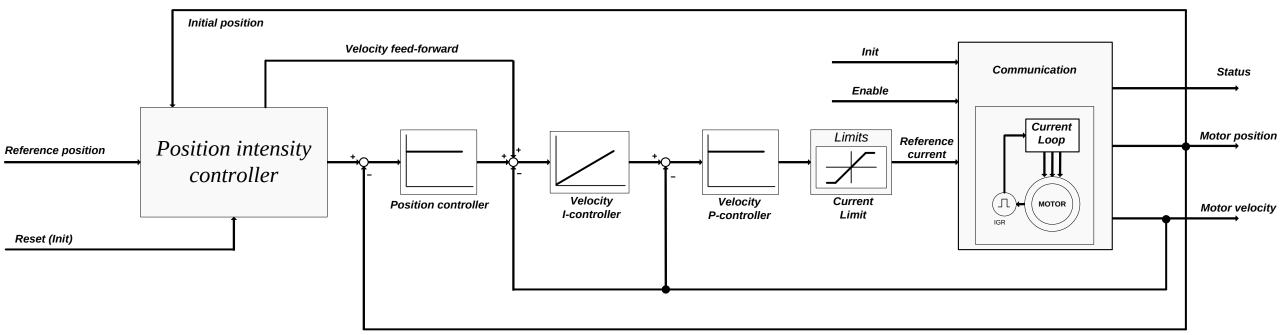

Figure 8 Position/velocity control loops

1. reference currents are id_ref = 5A, iq_ref = 0A for rotor positioning along the flux axis D;
2. one second pause for the exact positioning;
3. reset of the IGR's counter;
4. start the current loop, in other words wait for the reference value of iq_ref, the reference value of id_ref is equal 0A.

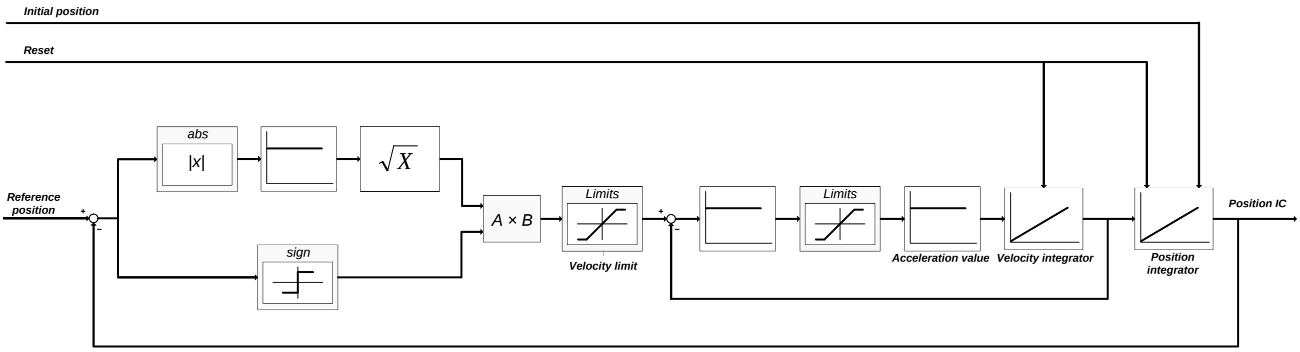

Figure 9 Position intensity controller

To ensure correct working of the position control loop when a step reference signals is applied a second order position intensity controller (Figure 9) has been developed.

The experimental results of position/velocity control loops as well as current control loop are shown in Figure 10. Experiments have been carried out on the linear drive without any loads. The position reference signal has been applied as the step signal.

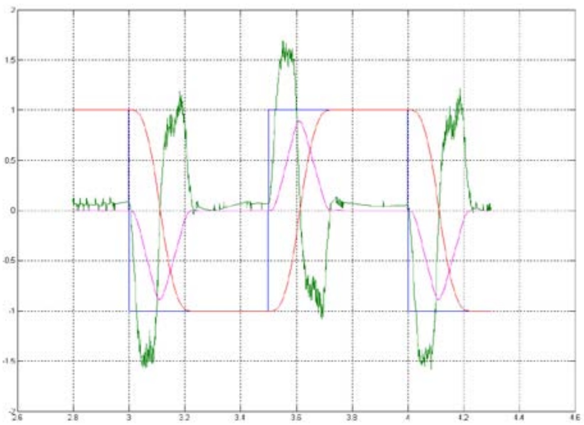

Figure 10 Experimental results: blue – reference position (±10 revolutions); red – actual position (±10 revolutions); magenta – velocity (±13000 rpm); green – current (±3,6A)

4.2 Force/Position control loops of modified actor

The structure of the force control system is shown in Figure 11.

The force control system has a subordinate structure. There is only one inner control loop – the current control loop. Such approach allows reaching the highest dynamical characteristics of the force control loop. Some successful attempts of using such structure are shown in the works of MIT-University [3].

The force control loop is controlled by the PD-regulator. The dotted feedbacks in Figure 11 are not taken into account when designing the PD-controller. This neglect can be made because of the high dynamics of the force control circuit. These feedbacks are considered as a disturbances and don't cause any instabilities in the system.

The step response of the force control loop is shown in Figure 12. The first sequence is 15 ms by the bandwidth of the force control loop of 50 Hz.

The position control system is shown in Figure 13. The above considered force control loop is the inner loop of the position control system.

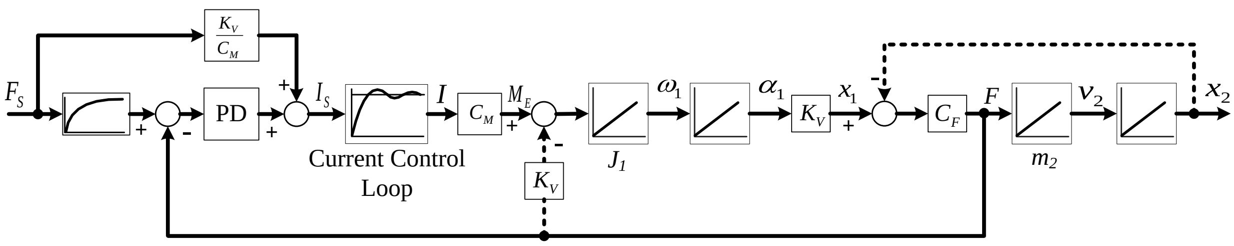

Figure 11 Structural scheme of the force control system, where CF – the coefficient of the spring rigidity (spring constant), KV – coefficient of the conversion of the rotational motion into the translational motion, CM – coefficient of the conversion from current to mechanical torque

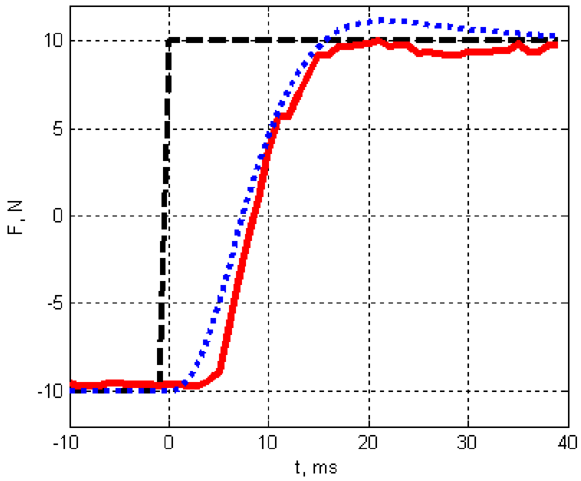

Figure 12 Step response of the force control loop: dotted line – modelling; solid line – experiment

The coefficient K_D determines the system damping. The coefficient K_P and the value F_G are the most interesting because their variation allows the achieving the specific properties of the position control system when getting into contact with environment. For example, by setting a small value of coefficient K_P the behaviour of the system in contact is elastic (low impedance, artificial spring). Another task – a precise position control with force saturation in the contact point – can be achieved by setting of higher value of coefficient K_P and a given value of F_G. Such case is illustrated in Figure 14, where the end-position is not reached as a result of an impact with an obstacle.

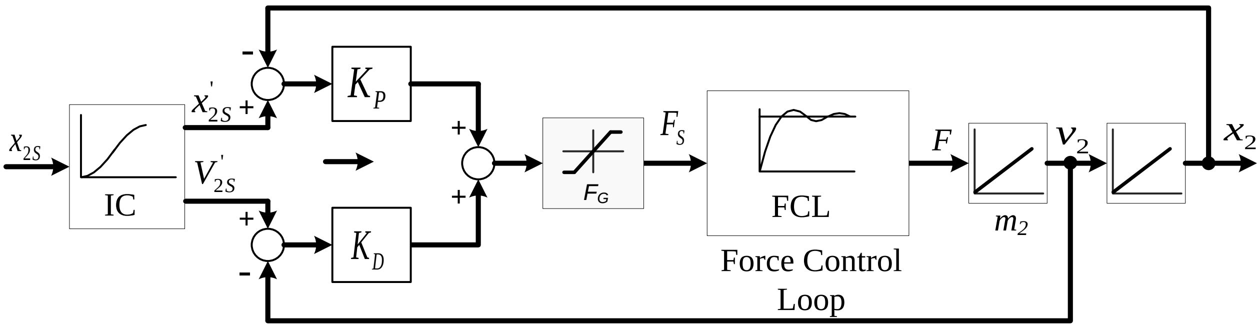

Figure 13 The position control loop

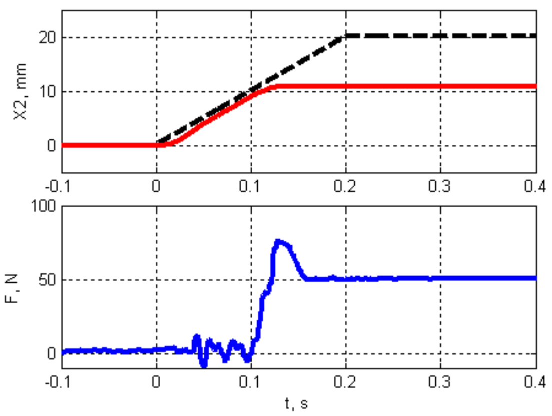

Figure 14 Impact with an obstacle by position control: dotted line – desired position; red line – actual position; blue line – force in the contact

5 Literature

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