Mateusz SAKÓW, Arkadiusz PARUS
FACULTY OF MECHANICAL ENGINEERING AND MECHATRONICS, INSTITUTE OF MECHANICAL TECHNOLOGY,
WEST POMERANIAN UNIVERSITY OF TECHNOLOGY
19 Piastów Ave., 70-310 Szczecin

Sensorless control scheme for teleoperation with force-feedback, based on a hydraulic servo-mechanism, theory and experiment

Abstract

Telemanipulation systems with force-feedback are being developed from early 70's. These devices were successfully applied for remote manipulation of objects at very large distances. These types of manipulator systems are also applied in hostile environments. This work includes development of a new approach to a control design in bilateral teleoperation with force-feedback. The new control scheme does not require the force sensor placed between the manipulator body and objects of an environment. Presented approach estimates the value of environmental force impact on the manipulator body by an inverse mechanical model of the Slave subsystem. Prediction of the inverse model requires information about the value of current position of a manipulator joint. Presented system uses model estimated on-line, during manipulation tasks. Research was carried out on a hydraulic servo-mechanism test stand. The work ends with the report from the test stand and conclusions.

Keywords: Force-feedback, telemanipulation, inverse modeling, prediction of model input.

1. Introduction

Telemanipulators with force-feedback have been developed since early 60's, when for the first time the problem was raised. These devices could be successfully applied for remote manipulation of objects on great distances. Such manipulators are applied in a hostile environment; when environment could be harmful to the operators of such systems. In terms of safe work, bilateral teleoperators are unparalleled between other manipulating devices, helping man with completion of difficult tasks. Telemanipulator systems with force-feedback, as it turned out, created many new problems in the form of mechanical manipulator structure, its drives, but also in a control scheme design. These problems are worth to be discussed and are analyzed almost in every paper about bilateral teleoperation devices [1-11].

Delay in the telemanipulators communication channel is an important problem. The delay is the main feature causing instability of such a system. Many designed control schemes focus on maintaining the stability and leveling effects of the delay in the communication channel [1-4, 6, 9, 12-18].

Transmittance of object experienced in the force-feedback channel by the operator of subsystem Master, during free motion of the Slave subsystem, is also a problem of standard sensory methods. The free motion of the Slave manipulator is understood as a motion without interaction between the Slave subsystem and the environment. Second type of transmittance experienced in the force-feedback channel by the operator of subsystem Master, during interaction between the Slave manipulator and the environment objects is, also present. This is a key factor, which tells the operator how well he can experience the environmental impact on the Slave manipulator joint or the extent to which it is distorted [9].

Described telemanipulators' systems belong to the group of Master-Slave systems with force-feedback. The manipulator of subsystem Master, in most of control schemes, is responsible for tracking an operator motion, which the operator interacts directly on master manipulators body. Subsystem Slave placed in hostile environment, usually in some distance from Master subsystem, generally is also a manipulator, similar to the subsystem Master in terms of kinematics, mass and dimensions. The criterion of mass and overall dimensions' similarity between both subsystems is often, however, not maintained. The primary task of manipulator Slave is trajectory tracking, which is transmitted from the Master manipulator side of the system. Manipulator Slave placed in a distance and performing manipulation operations is controlled by a master manipulator. Slave manipulator interacts with the environment, where in regular case, man should perform manipulation tasks. These interactions, which are the forces influenced by the impact of environment are transmitted back to the Master manipulator in the force-feedback communication channel. These forces are usually measured by force sensors – standard sensor control schemes. The force sensor placed between manipulator body and environmental objects, is the key factor of control schemes in the scientific literature [1-3, 7, 8, 10, 12, 13, 15, 16, 19, 20].

In 1966, William R. Ferrell in [1], presented the first work about master-slave manipulators, where forces were measured by the remote finger and were transmitted back to the operator. In [1], for the first time, the problem of time delays in communication channel has been raised. Most of conclusions are devoted to the issue of time delay in communication that mainly comes from the distance between master and slave subsystem. Delay feature was the primary cause of instability of such a system. The main result of this work was development of two control strategies that make possible to navigate the master subsystem, which was co-operating with remotely controlled slave manipulator under large delays in the communication channel.

Gunter Niemeyer in 1991 [2], discussed problems of telerobotics. Extensive work studied the existence of transmission time delays that affect the application of advanced robot control schemes for effective force-reflecting telerobotic systems, which would best exploit the presence of the human operator. The author of [2], introduced physically motivated, passivity based formalism which was used to provide energy conservation and stability guaranteed in the presence of transmission delays. Wave variables were utilized to characterize time delay systems and led to a new configuration of force-reflecting teleoperation control scheme. The author also presented an adaptive tracking controller, which was incorporated for the control of the remote robotic system, to improve the dynamics of the whole system perceived by the operator.

In 1992, Won S. Kim presented two papers summarizing his research [8, 16], the "shared compliant control" and the "Developments of New Force Reflecting Control Schemes and an Application to a Teleoperation Training Simulator". In the first paper the control scheme was incorporated into an advanced six degree of freedom force-reflecting telemanipulation system. With this system, like in the other papers, the author investigated the effect of time delay on human telemanipulation task performance. Shared compliant control enabled the operator to control the telemanipulator by having a compliant hand, which softens contact forces between the robot hand and objects of environment. The third and fourth novel schemes of force-reflecting control enable high force reflection gain: position-error-based force-reflection and low-pass-filtered force- reflection were both combined with shared compliance control from the previous work. Both presented control schemes enabled unprecedented high force reflection gains, with reduced bandwidth for dissimilar Master-Slave arms, when unity position scaling was used.

Dale A. Lawrence in 1993 [19], presented space application, as potential direction of application of telerobots, characterized by significant communication delays between operator commands and resulting robot actions at a remote site. A high degree of telepresence was desired to enable operators to perform teleoperation tasks safely, in outer space. This paper provided tools for quantifying teleoperation system performance and stability when communication delays are present. This paper introduced the novel four channel communication control scheme, which was of critical importance in achieving high performance telepresence in the sense of accurate transmission of environmental impedance to the operator.

In 1994, Yasuyoshi Yokokohji in [10], presented a new approach to analysis and design methods for master-slave teleoperation systems. The primary goal of this work was to develop a Master-Slave system that could provide good maneuverability. The proposed control scheme required accurate dynamic models of the master and slave arms, but neither parameters of the remote object, nor the operator dynamics was required.

Adaptive controllers were applied to telerobotics also by Wen-Hong Zhu, in [3]. The author presented the work about an adaptive motion - force controller which was developed for bilateral teleoperation systems. Both the Master and the Slave were subjected to independent adaptive motion and force controllers that assumed parameter uncertainty bounds. The states of the Master-Slave were sent to the Slave and Master as motion and force tracking commands, instead of control actions. Under the modeling assumptions for the human operator and the environment, the proposed teleoperation control scheme was stable in both types of work - free motion and flexible or rigid contact motion and was robust against time delays.

At the present time, scientists are implementing new algorithms into bilateral teleoperation systems, like neural network, fuzzy logic [21, 22] and frequency separation methods [6, 14], but they remain at the standard control scheme, based on force sensors placed between the Slave manipulator and the objects of environment.

In 2010, Ming-Kun Chang [22] introduced paper concerning pneumatic muscle actuators applied as the main drives of manipulator. Author mentioned that the pneumatic muscle actuators have the highest power/weight ratio and power/volume ratio among actuators of all types. Therefore, these drives can be even used in rehabilitation engineering. Ming-Kun Chang indicates a problem in achieving excellent control performance using classical control methods because of the compressibility of gas and the nonlinear elasticity of bladder containers causing parameter variations. The author presented a control scheme of high complexity, the adaptive self-organizing fuzzy sliding mode control. Its fuzzy sliding surfaces helped to reduce the number of fuzzy rules used. The self-organizing learning mechanism was employed to modify fuzzy rules online. The model-matching technique was adopted to adjust the scaling factors.

R. Moreau in 2012 [5], presented paper about a novel bilateral control scheme for pneumatic Master-Slave teleoperation systems that were actuated by on/off solenoid valves. A sliding mode approach, called the three-mode control scheme, was incorporated into a two-channel bilateral teleoperation architecture, which can implement a position–position, force–force or force-position control scheme. The proposed control design performance was experimentally verified on a 1-DOF pneumatic teleoperation system actuated by on/off valves. Experimental results showed high accuracies in terms of position and force tracking under free-space motion and hard contact motion in the teleoperation system. Another purpose of this paper was to demonstrate the possibility to improve the valve lifetime by increasing the number of control levels. To do this, a new control design, called the five-mode control scheme, was developed and compared with the three-mode scheme.

In 2013, S. Farokh Atashzar [6] raised the issue of designing telemanipulation devices used for remote rehabilitation. Problem of a haptics-enabled teleoperated rehabilitation system in the presence of communication delays was addressed. In a teleoperated rehabilitation system, communication delays introduced phase shift which may result in the task inversion phenomenon. To overcome the task inversion, a new type of projection-based force reflection algorithm was proposed, which was suitable for assistive and resistive therapy in the presence of irregular communication delays. Projection-based force-reflection algorithm was demonstrated to substantially improve stability characteristics of bilateral teleoperators with communication delays. However, the transient response of the projection-based force-reflection algorithms suffered from relatively slow force convergence. Thus, the high-frequency component of the reflected force was lost during the initial phase of contact with the environment, which had a strong negative effect on the haptic perception of the environmental stiffness and texture. In 2015, S. Farokh Atashzarthis [14], introduced, a new type of algorithm, which solved the aforementioned problem. The new algorithm was based on the idea of separation different frequency bands in the force-reflection signal and apply the stock algorithm principle to the low-frequency component, while reflecting the high-frequency component directly. Paper results confirmed that the new algorithms fundamentally improve force convergence without a negative effect on stability of the teleoperator system with communication delays.

For the last twenty years, domain of sensor-less bilateral teleoperators is dominated by piezoelectric crystals. Piezoelectric crystals can work at the same time as a body, an actuator and a force sensor, especially, when devices are made of a large group of single crystals. Piezoelectric crystals are the primary actuators in telemicro-manipulation domain. Main advantages of using piezoelectric crystals as actuators is that, that these materials deform with high velocities and generate relatively high forces. Researchers focus not only on control schemes aimed at better stability, but also on the quality of the environment reflecting effect on actuators. Scientists efforts are also concentrated on developing special mechanisms, that would enable better cooperation between the operator and the master manipulator.

Bilateral systems with force-feedback, used to be fitted with sensors of relatively large susceptibility and substantial dimensions. Current research points at piezoelectric sensors for the manipulation of extremely small objects. Manipulation is also executed with piezoelectric elements which are used as drives. The model discussed in the present paper is used for force estimation in the force feedback-communication channel. But it has to be mentioned, that in this methods piezo-crystals are considered as flexible mechanical bodies. This important feature distinguishes the method presented in this work, between those presented so far in [23-30]. There are couple of works, that are worth considering during analysis of sensor-less methods in bilateral teleoperation.

In [24, 26, 27] Rakotondrabe mainly focuses on the dynamic self-sensing piezoelectric actuators. The measuring technique proposed by Rakotondrabe was subsequently used for a closed-loop control. Aiming to obtain a novel control scheme that estimates the transient and steady-state modes of the displacement. The author extended a previous static self-sensing scheme by adding a dynamic part. Micky Rakotondrabe, in 2011, also developed a new micro-gripping device, dedicated to micromanipulation. The micro-gripper presented both high range and high positioning resolution. The principle of the micro-gripper was based on the combination of the thermal actuation and the piezoelectric actuation methods. To improve the performance of the micro-gripper, its actuators were modeled and a control law for both the position and the manipulation force was synthesized afterwards.

Micky Rakotondrabe continued his studies and, in 2015, presented his work about a self-sensing technique, using an actuator as a body, a drive and a sensor at the same time. This was only possible for actuators with a physically reversible principle, such as piezoelectric materials. The main novelty of the paper was that, that both displacement and force signals can be estimated simultaneously. This allowed building of a feedback control using one of these two signals, with a display of the other signal.

This paper presents a new approach to a control design referring to bilateral teleoperation with force-feedback communication channel. New control scheme does not require force sensors, which are placed between the manipulator body and the environment. Every mechanical part of the manipulator is considered as a perfectly rigid element. There are no flexible bodies in the structure of presented manipulator considered during theoretical analysis and experiment. New approach calculates the values of environmental forces impact on manipulator body, by an inverse mechanical model of Slave subsystem. The input of the model requires information about the value of current position of the manipulator joint. The model included in control design is, however, nothing new. The perfect examples of sensor-less teleoperators are piezo-ceramic micromanipulators mentioned earlier in this paper. Presented system and its control unit, are also based on a model calculated in real time, during manipulation tasks. The model uses different control signal then models used in micromanipulation. The mechanical structure of the manipulators is also totally different. Micromanipulators are built of elements that act as a body, a drive and a sensor at the same time, like it was mentioned in the literature analysis above. In the method presented here, the model uses only a position control signal, transmitted from the position sensor unit into the controller.

In the presented paper, the system does not measure environmental force impact, but estimates its value based on the control signals of the slave controller and current Slave manipulator position. New control scheme presented in this paper, considers the manipulator as a set of perfectly rigid bodies. This feature was probably never mentioned before in the scientific literature, in case of bilateral teleoperators with one exception. The exception is one of control schemes, based on bilateral position error, presented by Won S. Kim in [8]. In this paper, the system calculates the value of force-feedback in communication channel, based on control signals and current position of the subsystem Slave. In Kim's method, force was calculated by difference between the positions from the Master and Slave subsystems, in each joint. Mechanical structure of the manipulator, based on Kim's control scheme, was considered in bilateral control design as made from perfectly rigid objects, but a susceptible element between the manipulator body and the object of environment was also included.

2. Sensor-less control scheme for teleoperation with perfectly rigid bodies

The presented sensor-less control scheme for bilateral teleoperation consists of two subsystems - the Master subsystem and the Slave subsystem. Both subsystems, the Master (a) and the Slave (b) are considered as simple rigid objects described by their inertia, and are presented in Fig. 1.

These manipulator bodies move in an environment described by the dissipative element h_e. The damper in its simplification represents an environment of air. The manipulators' bodies move without friction between them and the world frame. Master subsystem acts as a motion scanner, which sends the information about its own position x_m to the control unit of the slave manipulator.

Master subsystem motion depends on three forces applied to the body of Master manipulator. The first is the gravity, described as $G_m = M_m g$, where g is the acceleration of gravity and M_m is the mass of the body. The second force is the force applied by the operator F_h to the body of Master manipulator. The third force applied to the body of Master manipulator is F_{es}, which is transferred in communication channel from the Slave subsystem. For theoretical analysis transmittance of the Master subsystem actuator, resisting operators motion is not considered.

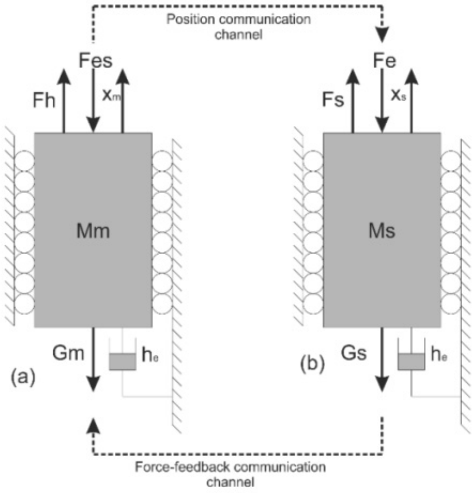

Fig. 1. Graphical presentation of models: master subsystem (a), the slave subsystem (b)

During analysis, the Slave subsystem is a duplicate of the Master subsystem, under conditions of kinematics, dimensions and mass. This subsystem also moves in the same environment as the Master subsystem. The Slave manipulator is described by its mass – M_s, gravity force G_s, trajectory – x_s, control force F_s which is applied by the control unit (theoretically including the Slave actuator), and the environmental impact represented by force F_e. Transfer function B_i, which describes dynamics of both manipulators, can be presented as a formula (1):

$$B_i = \frac{1}{(M_i s + h_e)s}, \tag{1}$$

where i - index, m for Master subsystem, s for Slave subsystem, s - Laplace operator, M_i - mass. Additional designations used in this work are included in Tab. 1.

Tab. 1. Description of additional symbols used in section 2

Designation	Description
F_{sm}	Estimated value of the force generated by the drive of the Slave subsystem, during free motion of manipulator a Slave.
$e(s)$	Position error in motion control unit of the Slave manipulator.
$K(s)$	Transfer function, which describes the controller transmittance of the Slave manipulator

Standard two channel telemanipulation system using force sensor, can be represented as a block diagram shown in Fig. 2.

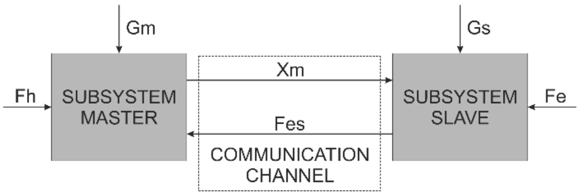

Fig. 2. Block diagram of standard sensory method

In Fig. 2, system senses the environmental force impact, by the force sensor and sends the value of this force, back to the Master manipulator through the force-feedback communication channel F_{es}.

In the paper, the system does not measure environmental force impact, but estimates its value based on the control signals of the slave controller and the current Slave manipulator position. Modified structure of the telemanipulation system is presented in Fig. 3.

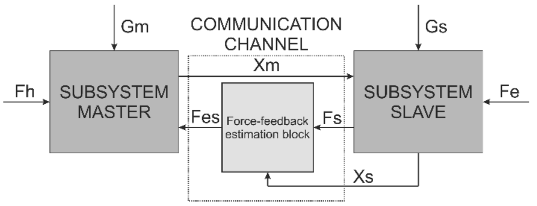

Fig. 3. Block diagram of the presented method with the force-feedback estimation block

In Fig. 3, the system has an additional block, the estimation block. It calculates the force of environmental impact based on the force value computed by the model of the Slave subsystem. The force-feedback estimation block, subtracts measured control signal of the drive, from the one estimated by the model in free motion. This measured force could be represented by a hydraulic pressure, a voltage or, like in this paper, by a hydraulic valve current. The modified system is shown in details in Fig. 4.

The primary problem of the methods, which use force sensors and rotary joints is that, that the control unit needs a large amount of force sensors placed on the manipulator arm. This feature is crucial for delivering correct value of environmental torque impact in each rotary joint. The method used in the paper computes the value of environmental force impact on the slave manipulator to the operator, which is measured independently in in each joint of the Slave manipulator in the drive path. Presented system requires as many sensors of current, voltage or pressure, as many degrees of freedom are included in the Slave manipulator structure. It makes no difference for the method if rotary or linear joints are used.

The analysis of the components of the system transmittance, proves that the system equipped in perfect inverse model, will send the exact value of the impact of the environment on the slave manipulator in the force-feedback communication channel. During its the free motion, the system delivers zero value of force in the force-feedback communication channel. The system also delivers the correct value of force even in the rigid contact situation between the environment object and the Slave manipulator body. These features are always a serious problem in standard direct force sensing methods.

The analysis of the simplified system of Fig. 4 should confirm theses presented in the paragraph above. The first characteristic transmittance, which describes the Slave side of the telemanipulation system, is a transmittance without impact of gravity force and environmental force on the Slave manipulator - Fig. 4. The gravity force and the environmental force are described by equations (2):

$$G_s = 0;\ F_e = 0. \tag{2}$$

To investigate the effectiveness of the method it is required to find the Slave subsystem closed-loop and the inverse model transmittances – see Fig. 4. The Slave subsystem transmittance needs to be reduced to a simple transfer function. The Slave transfer function will be described by the relation of two signals x_m, which is the position of Master send to Slave and x_s, which is the position of Slave. The transmittance x_s/x_m can be presented as formula (3):

$$\frac{x_s(s)}{x_m(s)} = \frac{K(s)}{(M_s s+h_e)s+K(s)}. \tag{3}$$

Formula (3) describes the closed-loop system of the Slave manipulator, including transfer function of the position controller K(s). It is possible to use many structures of regulators like simple proportional P, PI or even PID, therefore the controller transfer function is undefined for the transmittance analysis. However, a different controller structure would not change the results of transmittance analysis.

In continuation of transmittance analysis, the slave subsystem closed-loop transfer function is determined as (3). Now the second step of transmittance analysis is carried out. The transmittance should describe properties of the system that includes the inverse model of force-feedback estimation block and the slave closed-loop subsystem. The transmittance is defined by the ratio of the estimated value of the force F_{sm} generated by the drive during free motion and the Master position – x_m. Transmittance F_{sm}/x_m is presented by formula (4):

$$\frac{F_{sm}(s)}{x_m(s)} = \frac{K(s)(M_s s+h_e)s}{(M_s s+h_e)s+K(s)}. \tag{4}$$

Formula (4) describes one of the two characteristic transfer functions, i.e. the function that is responsible for subtraction of the simulated control signal by the inverse model from the measured control signal.

Next step requires finding the transmittance of the Slave subsystem closed-loop, which senses the control signal F_s computed by the regulator block $K(s)$. Theoretically, this signal is just the control force applied to the body of the Slave manipulator. In practice, the control signal on the Slave side could be a voltage, a current or a hydraulic valve current, as it is presented in the fourth section of this paper. To write this transfer function, a solution of two equations, presented as (5), is required:

$$\begin{cases} F_s = K(s)e(s) \\ x_s = \frac{F_s}{(M_s s+h_e)s} \end{cases}, \tag{5}$$

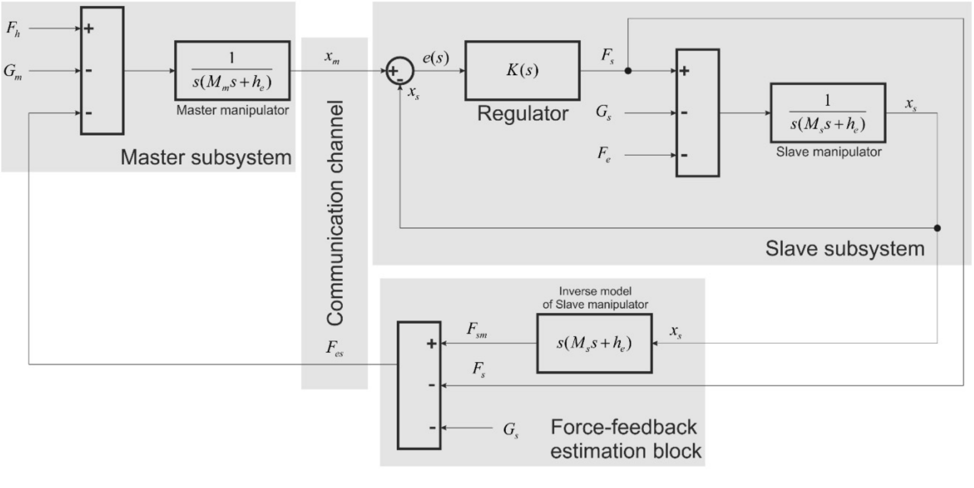

Fig. 4. Detailed block diagram of the system used for the proofs and analysis

where $e(s)$ is a Slave subsystem position error, described as $e(s) = x_m(s) - x_s(s)$. The solution of equations (5) can be written as a ratio $F_s(s)/\,x_m\,(s)$ – formula (6):

$$\frac{F_s(s)}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}. \tag{6}$$

The structure of the equation (6) is the same as in transmittance (4). This means that subsystem Slave, during its free-motion in remote environment, gives zero value in the force-feedback communication channel. This is confirmed by the transmittance difference, which is represented as force-feedback estimation block in Fig. 4 - equation (7):

$$F_{es} = \frac{F_s(s)}{x_m(s)} - \frac{F_{sm}(s)}{x_m(s)} = 0. \tag{7}$$

For the operator of a system, which uses presented method, this situation is comfortable, but requires very accurate inverse model of Slave subsystem. It is important in theoretical analysis of ideal system presented in Fig. 4, to show that the subsystem Slave, which is under influence of the environmental force, sends to the operator exact value of the force of environmental impact.

In the second part of transmittance (4) and (6) analysis external forces are considered. These forces were omitted during the first step of analysis, to proof that system in free-motion situation correctly estimates a force value in force-feedback communication channel. Slave subsystem in Fig. 4, including external forces, is described by two new equations (8) and (9):

$$\frac{F_{sm}(s) - G_s}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}, \tag{8}$$

$$\frac{F_s(s) - G_s - F_e}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}. \tag{9}$$

Subtracting equations (8) and (9), yields (10):

$$F_s(s) - G_s - F_e - F_{sm}(s) + G_s = 0. \tag{10}$$

After simplifying equation (10), equation (11) is obtained:

$$F_s(s) - F_{sm}(s) = F_e, \tag{11}$$

where the difference $F_s(s) - F_{sm}(s)$ corresponds, according to the control scheme of Fig. 4, to the signal of force-feedback communication channel F_{es}, presented as equation (12):

$$F_{es} = F_e. \tag{12}$$

As it is seen, if a highly accurate mathematical model of Slave subsystem can be build, it is possible to transmit the value of the environmental force impact to the operator. Note, however, that getting a model that exactly corresponds to the real object, is in practice very difficult or even impossible, so the value of estimated environmental force in the force-feedback communication channel, using presented system, will strongly depend on the accuracy of this model.

3. Inverse modelling method with prediction

The inverse model used for prediction of the input signal of controlled object, based on the output signal, has one main disadvantage. There is a delay between cause and effect. Force/pressure from actuator is causing motion of the manipulator body and the measured motion output is out of phase with respect to the input signal. In the analyzed case, it is a current of a hydraulic valve coil. It is obvious that there are also other reasons of the delay, like a measurement of output and input signals with some delay. But if input and output signals are measured with comparable delays, this detail is not a problem, and could be negligible. Presented method of inverse modelling is focused on prediction of current, of a hydraulic valve based on the position of the hydraulic cylinder. Both the position of hydraulic actuator and the valve current are presented in Fig. 5.

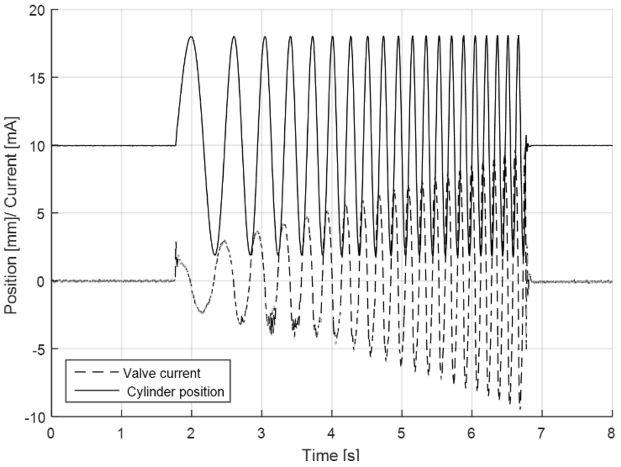

Fig. 5. Measured valve current and manipulator body position without filtration

In Fig. 5, it can be easily seen, that position of manipulator body is delayed and is out of phase with respect to the hydraulic valve current. This important feature eliminates the method in its simple form presented in section two of this paper. Simple inverse model is therefore not precise enough for correct online prediction of the input based on the output signal. To deal with this problem, it is proposed to build and identify inverse prediction models based on a simple prediction control structures, which are prediction controllers. The prediction controllers are commonly used in bilateral teleoperation systems [2, 12, 31].

Structure of the feedback channel for predictive control is generally known. In this paper, standard feedback prediction channel is used to predict the input and the output of the inverse model during an identification procedure and operation of the system. Based on these assumptions, simple force-feedback estimation block from Fig.4 was modified by including input and output prediction blocks. For details see Fig. 6.

The structure from Fig. 6 is used in two cases. During inverse model identification, delay parameters like T_p, are set by the system designer, providing predicted input to inverse model block and predicting the model output. The current estimated by the inverse model block, is out of phase with respect to the input signal back in time. The low-pass filter with parameter T_c was used to minimize the high frequency noise in the measured signal, moreover, it was responsible for the phase shift relative to the base current signal. Using in force-feedback estimation path two prediction blocks and a filter, allows the method to calculate signals and shift them to the same phase in time.

In the control unit, force-feedback estimation block works in the similar way, but prediction block allows the system to minimize the delay between the measured and predicted current. During the analysis of prediction blocks used in the force-feedback estimation block, only one issue appeared, which turned into advantage. The problem of overshooting the current estimation values during the rapid changes of the inverse model input signals. Identification carried out on the structure from Fig. 6, proved that the overshoot of the predicted valve current during free-motion, reflects the measured current better than using simple linear model based on derivative. This method does not increase the noise amplitude and, as can be seen in Fig. 9 and Fig. 10, can predict the current with high accuracy even based on current inverse linear model. Summarizing, the structure from Fig. 6, used in the identification procedure, is quite similar to the structure used in control unit for online current estimation.

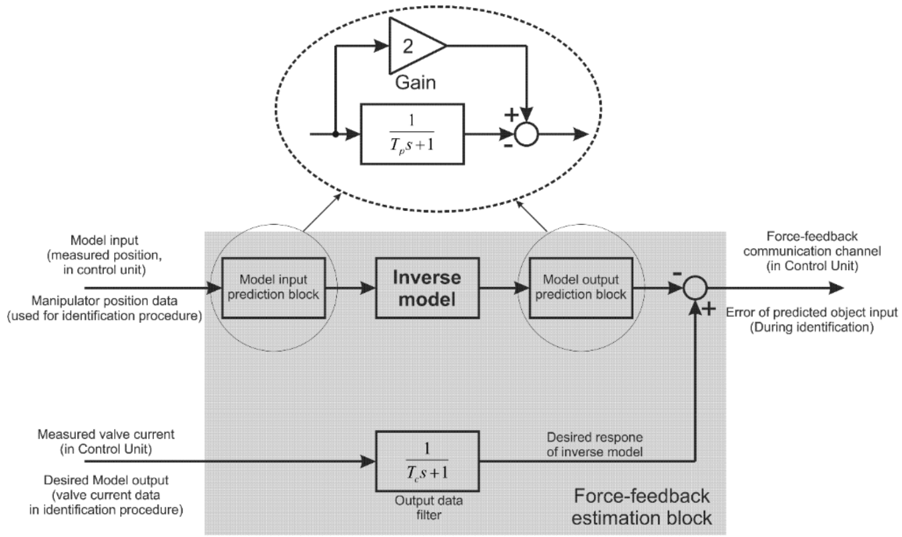

Fig. 6. Modified force-feedback estimation block, including model input/output prediction blocks, used in control unit and identification procedure

The only difference is that, that during identification procedure, only denominator's polynomial coefficients of inverse model are searched. Some parameters of the inverse model remain constant during online calculation in the control unit of the bilateral teleoperation system.

4. The experiment

A test-stand was prepared for the experiment. The Slave subsystem presented in Fig. 7 includes one hydraulic servo-mechanism.

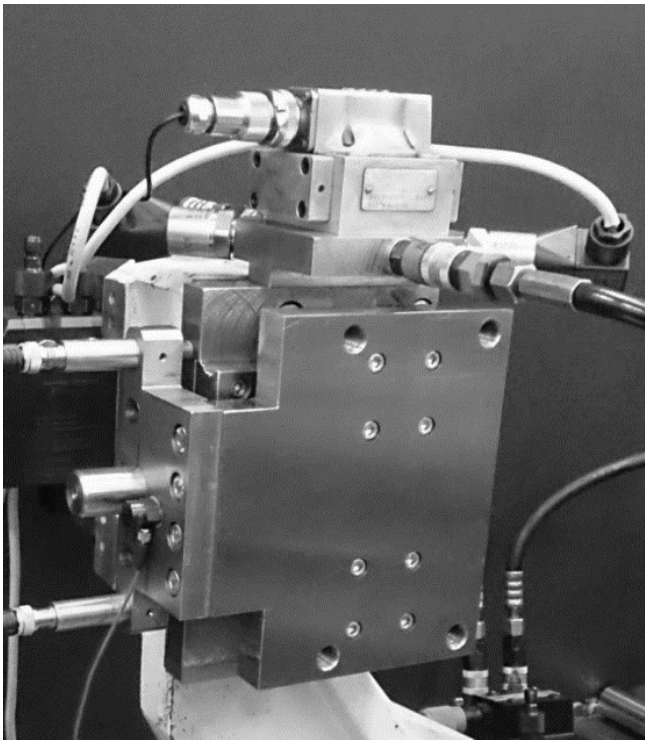

Fig. 7. Test-stand used for research and analysis

Photography from Fig. 7 does not show, the idea of the test-stand, so additionally the exploded view is shown in Fig. 8.

Hydraulic servo-mechanism Slave subsystem was controlled by 760series Moog servo valve. This important and expensive part, allow the system to track position with high accuracy. The accuracy of position tracking is a key factor when bilateral teleoperation systems are compared. This valve during tests has proven its usefulness, not only in quality of position tracking but also in force applying, to the rigid environmental object. This forces where proportional to the value of valve current. The value of the current depends on position error between Slave subsystem and the set-point position from the controller (Master device).

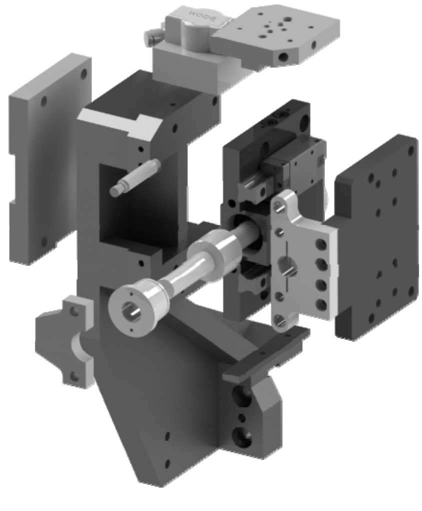

Fig. 8. The exploded cad view of device

The system was also equipped with two independent pressure sensors measuring hydraulic pressure in both hydraulic actuator chambers. The first idea was the control unit, which calculates the value of the force in the feedback communication channel based on the difference between simulated and measured hydraulic pressure. But as it turned out, measured pressure was distorted by many unmeasured factors. This caused problems with identification of the pressure estimating inverse model. The idea of using the pressure estimating inverse model was abandoned temporarily.

Hydraulic pressure sensors were not the only sensor devices in Slave subsystem. There were also two displacement sensors for measuring actual position of manipulator body. Both displacement sensors measured the same displacement, and the controller calculated an average position.

In the structure composition of the Slave subsystem were also included two acceleration sensors. The first sensor was attached to the base body. The second sensor measured acceleration of the movable Slave manipulator body. In these tests, acceleration sensors have not been used.

At this test stand, series of tests were carried out. The first test showed the ability of position tracking by the Slave subsystem during free motion situation, for the variable operating frequencies as a reference to a chirp signal. The chirp signal was changing its frequency in 5 seconds from 1 Hz to 5 Hz. It was mentioned before, that the system is able to track position with high accuracy. This ability finds its proof in Fig. 9.

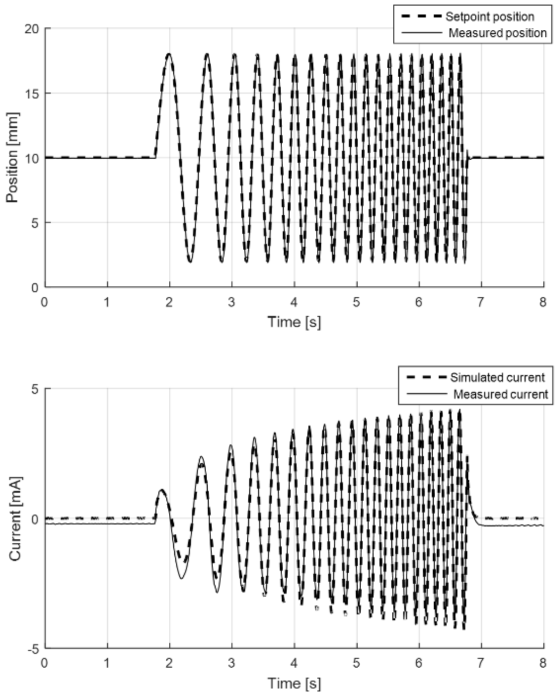

Fig. 9. First test in position tracking and online simulation of valve current

The first test proved two things. First, that the tested hydraulic bilateral teleoperation system is capable of tracking position with high accuracy, even when using standard proportional controller, based on a position error control scheme. The second, that there is an ability to calculate the valve of current by the inverse prediction model. It is presented on lower plot in Fig. 9.

The lower plot of the current confirms that Master - Slave systems with force-feedback do not require use of force sensors placed between manipulator body and the object of the environment. The environmental force impact could be calculated by the force-feedback estimation block. It subtracts measured current from its value predicted by the inverse model. Comparatively good accuracy is obtained.

In the second test responses of the system and the inverse model to a step signal were measured. Plots from this test are presented in Fig. 10.

The first and the second test proved that presented bilateral teleoperation system is capable to track set-point position and predict its input signal (current) – Fig. 9 and Fig. 10. In the first test, it was a chirp signal, in the second test it was a step signal.

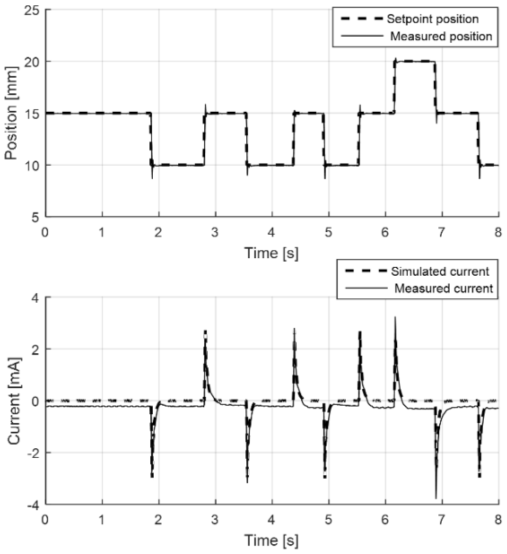

Fig. 10. Second test in position tracking and online simulation of valve current

The third and the last test, presents how the system can estimate the value of environmental force in rigid contact situation. Position and current values are presented in Fig. 11.

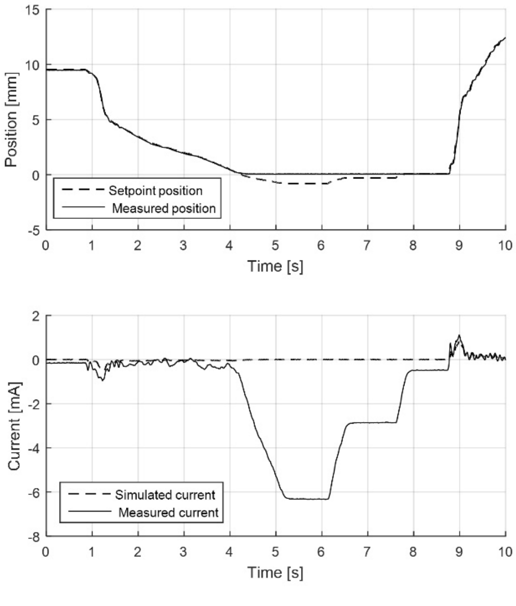

Fig. 11. Third test in position tracking and online simulation of valve current

In the upper plot, it is possible to see the position error, which testifies the contact between the manipulator body and a rigid object. The error has noticeable values between 4 s and almost 9 s. The same situation, the proportional difference can be seen in the current plot below. As it was mentioned before, force-feedback estimation block predicts the force-feedback value, based on the difference of two signals. These are the measured and filtered current, and the current predicted by the inverse model. Accordingly converting this difference, it is possible to compare it with the converted hydraulic pressure. Comparison is presented in Fig. 12.

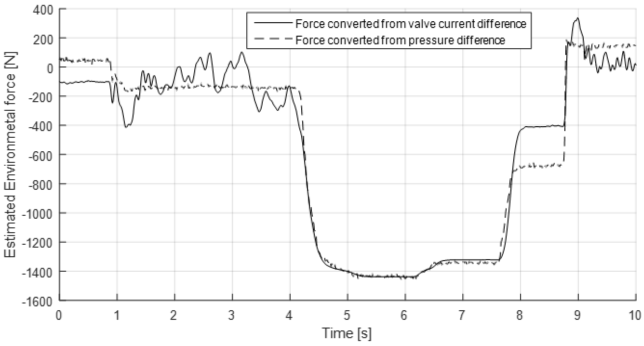

Fig. 12. Comparison of force estimates obtained: using pressure difference and using the value of force-feedback estimation block

Fig. 12 presents the greatest advantage of application of a sensor-less method discussed in this paper. The delay between measured and predicted force/pressure is unnoticeable. Another important advantage is stability, which is maintained during rigid contact. This finds its proof also in Fig. 12. It is important to mention also, that this system was tested without delays in the communication channel. These delays were not considered during analysis in all tests. An important drawback of this system is surely the mechanical part. Error of spool adjustment in the position of the servo valve with zero cover, caused a relatively important distortion of the estimated force. Also, the friction between cylinder and chamber, could be noticed on runs of the converted hydraulic pressure difference and the estimated value of force-feedback. These problems need to be overcome, to improve the quality of operation of the presented bilateral teleoperation system in future.

5. Conclusions

This paper presents a new approach to a control design in bilateral teleoperation with force-feedback. New control scheme does not require a force sensor placed between the manipulator body and objects of environment. The new approach was described in detail. Also, the theoretical transmittance analysis of the system was presented.

This work proved that the hydraulic servo mechanism, based on servo-valve, can track operator position with high accuracy. The system, based on a sensor-less force-feedback prediction method, uses an inverse model of the Slave manipulator. This important feature is an innovation, not known from other literature sources. Communication delays were not considered. The system proved its functionality during various tests, even maintaining the stability during contact with highly rigid environment object.

On further works it is planned to improve the mechanical part of the project, which was the main reason of distortion of force transmitted in the feedback loop. In future, the system will be expanded by adding other control schemes presented in scientific literature. System performance verification will be carried out, with delays included in the communication channel.

The work was carried out as part of PBS3/A6/28/2015 Fri. "The use of augmented reality, interactive voice systems and operator interface to control a crane", financed by NCBiR.

6. References

[1] Ferrell W. R.: “Delayed Force Feedback,” Human Factors: The Journal of the Human Factors and Ergonomics Society, vol. 8, no. 5, pp. 449-455, October 1, 1966, 1966.

[2] Niemeyer G. and Slotine J. J. E.: “Stable adaptive teleoperation,” Oceanic Engineering, IEEE Journal of, vol. 16, no. 1, pp. 152-162, 1991.

[3] Wen-Hong Z. and Salcudean S. E.: “Stability guaranteed teleoperation: an adaptive motion/force control approach,” Automatic Control, IEEE Transactions on, vol. 45, no. 11, pp. 1951-1969, 2000.

[4] Hyun Chul C., Jong Hyeon P., Kyunghwan K. and Jong-Oh P.: "Sliding-mode-based impedance controller for bilateral teleoperation under varying time-delay." pp. 1025-1030 vol.1.

[5] Moreau R., Pham M. T., Tavakoli M., Le M. Q. and Redarce T.: “Sliding-mode bilateral teleoperation control design for master–slave pneumatic servo systems,” Control Engineering Practice, vol. 20, no. 6, pp. 584-597, 6//, 2012.

[6] Atashzar S. F., Polushin I. G. and Patel R. V.: "Projection-based force reflection algorithms for teleoperated rehabilitation therapy." pp. 477-482.

[7] Arcara P., Melchiorri C. and Stramigioli S.: "Intrinsically passive control in bilateral teleoperation mimo systems." pp. 1180-1185.

[8] Kim W. S.: "Developments of new force reflecting control schemes and an application to a teleoperation training simulator." pp. 1412-1419 vol.2.

[9] Arcara P. and Melchiorri C.: “Control schemes for teleoperation with time delay: A comparative study,” Robotics and Autonomous Systems, vol. 38, no. 1, pp. 49-64, 1/31/, 2002.

[10] Yokokohji Y. and Yoshikawa T.: “Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment,” Robotics and Automation, IEEE Transactions on, vol. 10, no. 5, pp. 605-620, 1994.

[11] Saków M., Pajor M. and Parus A.: “Estymacja siły oddziaływania środowiska na układ zdalnie sterowany ze sprzężeniem siłowym zwrotnym o kinematyce kończyny górnej,” Modelowanie Inzynierskie, vol. 58, pp. 113-122, 2016.

[12] Sheridan T. B.: “Space teleoperation through time delay: review and prognosis,” Robotics and Automation, IEEE Transactions on, vol. 9, no. 5, pp. 592-606, 1993.

[13] Jong Hyeon P. and Hyun Chul C.: "Sliding-mode controller for bilateral teleoperation with varying time delay." pp. 311-316.

[14] Polushin I. G., Takhmar A. and Patel R. V.: “Projection-Based Force-Reflection Algorithms With Frequency Separation for Bilateral Teleoperation,” Mechatronics, IEEE/ASME Transactions on, vol. 20, no. 1, pp. 143-154, 2015.

[15] Munir S. and Book W. J.: "Internet based teleoperation using wave variables with prediction." pp. 43-50 vol.1.

[16] Kim W. S., Hannaford B. and Fejczy A. K.: “Force-reflection and shared compliant control in operating telemanipulators with time delay,” Robotics and Automation, IEEE Transactions on, vol. 8, no. 2, pp. 176-185, 1992.

[17] Anderson R. and Spong M. W.: “Bilateral control of teleoperators with time delay,” Automatic Control, IEEE Transactions on, vol. 34, no. 5, pp. 494-501, 1989.

[18] Anderson R. and Spong M. W.: "Asymptotic stability for force reflecting teleoperators with time delays." pp. 1618-1625 vol.3.

[19] Lawrence D. A.: “Stability and transparency in bilateral teleoperation,” Robotics and Automation, IEEE Transactions on, vol. 9, no. 5, pp. 624-637, 1993.

[20] Hastrudi-Zaad K. and Salcudean S. E.: "On the use of local force feedback for transparent teleoperation." pp. 1863-1869 vol.3.

[21] Shih M. C. and Ma M. A.: “Position control of a pneumatic cylinder using fuzzy PWM control method,” Mechatronics, vol. 8, no. 3, pp. 241-253, 4//, 1998.

[22] Chang M. K.: “An adaptive self-organizing fuzzy sliding mode controller for a 2-DOF rehabilitation robot actuated by pneumatic muscle actuators,” Control Engineering Practice, vol. 18, no. 1, pp. 13-22, 1//, 2010.

[23] Ishikiriyama Y. and Morita T.: “Improvement of self-sensing piezoelectric actuator control using permittivity change detection,” Journal of Advanced Mechanical Design, Systems, and Manufacturing, vol. 4, no. 1, pp. 143-149, 2010.

[24] Rakotondrabe M., Ivan I. A., Khadraoui S., Lutz P. and Chaillet N.: “Simultaneous Displacement/Force Self-Sensing in Piezoelectric Actuators and Applications to Robust Control,” Mechatronics, IEEE/ASME Transactions on, vol. 20, no. 2, pp. 519-531, 2015.

[25] Khadraoui S., Rakotondrabe M. and Lutz P.: “Interval Modeling and Robust Control of Piezoelectric Microactuators,” Control Systems Technology, IEEE Transactions on, vol. 20, no. 2, pp. 486-494, 2012.

[26] Rakotondrabe M., Ivan I. A., Khadraoui S., Clevy C., Lutz P. and Chaillet N.: "Dynamic displacement self-sensing and robust control of cantilever piezoelectric actuators dedicated for microassembly." pp. 557-562.

[27] Rakotondrabe M. and Ivan I. A.: “Development and Force/Position Control of a New Hybrid Thermo-Piezoelectric MicroGripper Dedicated to Micromanipulation Tasks,” Automation Science and Engineering, IEEE Transactions on, vol. 8, no. 4, pp. 824-834, 2011.

[28] Takigami T., Oshima K., Hayakawa Y. and Ito M.: "Application of self-sensing actuator to control of a soft-handling gripper." pp. 902-906 vol.2.

[29] Wei Tech A., Khosla P. K. and Riviere C. N.: “Feedforward Controller With Inverse Rate-Dependent Model for Piezoelectric Actuators in Trajectory-Tracking Applications,” Mechatronics, IEEE/ASME Transactions on, vol. 12, no. 2, pp. 134-142, 2007.

[30] Yuguo C.: "Self-Sensing Compounding Control of Piezoceramic Micro-Motion Worktable Based on Integrator." pp. 5209-5213.

[31] Smith O.: “Closer control of loops with dead time,” Chemical Engineering Progress, vol. 53, no. 5, pp. 217-219, 1957.

Received: 04.09.2016 *Paper reviewed* *Accepted: 02.11.2016*

Mateusz SAKÓW, MSc, eng.

Mateusz Saków started his higher education in 2010, received the B.S. degree in Mechatronics Engineering from West Pomeranian University, Szczecin in 2013. In 2015 received the M.S. degree in Mechanical Engineering also received from West Pomeranian University, Szczecin. His research interests include bilateral teleoperation systems and telemanipulation. From 2015 PhD student in Department of Mechatronics Systems. From 2015 a student member of ASME.

e-mail: mateusz.sakow@zut.edi.pl

Arkadiusz PARUS, DSc, PhD, eng.

PhD degree in technical sciences in the field of automation and robotics obtained in 2007, a post-doctoral degree in 2013. His research interests are focused on the problem of the suppression of harmful vibrations occurring during machining. He took part in the design of various types of vibration absorbers based on magnetic, electrodynamics and piezoelectric principle. His research interests include systems for suppressing vibration of the work-piece as well as the cutting tool.

e-mail: arkadiusz.parus@zut.edu.pl