Self-sensing Teleoperation System Based on 1-dof Pneumatic Manipulator

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Mateusz Saków, Karol Miądlicki, Arkadiusz Parus

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Abstract:
Paper presents a novel approach to a control design of bilateral teleoperation systems with force-feedback. The problem statement, analysis of research achievements to date, and the scope of the study are presented. The new design of a control unit for a master-slave system with force-feedback is presented on a simple and ideal 1-DOF bilateral teleoperation system. System control unit was based on an inverse model. The model was used to reduce value of force in the force-feedback communication channel, that the system might generate in free-motion. A substantial part of the paper is focused on the development of a mathematical model covering phenomena occurring in the investigated control scheme. The new approach was validated on a test-stand of a rotating non-linear pneumatic manipulator arm. Two linear pneumatic actuators were used in the drive system. The paper presents the modeling procedure of the experimental setup and the model used in the study. Three experiments are described to demonstrate the new control approach to master-slave objects with force-feedback. The paper contains conclusions regarding the control system and the experimental setup.

Keywords: *telerobotics, modeling, inverse problems, manipulators*

1. Introduction

Researcher's attempts to ensure safe operation of various machines have led to the development of master-slave control systems with force-feedback. Most master-slave systems are unilateral; i.e. a device that is being controlled (slave) should behave exactly as the device that controls it (master) [53–57]. However, as research continued, it was noticed that the operator that enters into interaction with the master subsystem/manipulator should also be able to feel the precise effect of the environment on the slave subsystem side. The problem poses significant challenges in its practical application, due to large distances and the inevitable time delay [1–19].

The applications of master-slave systems are widespread, including performing tasks in environments hostile to man, contaminated sites, in the depths of oceans and seas, radioactive interiors of nuclear power stations, and even other applications like medical rehabilitation. This specific branch of robotics faces many challenges that have been tackled by scientists all over the world for many years.

The main problem that arises in the communication channel between actuation devices are delays that inhibit their communication. The problem is particularly pronounced while sending information over large distances. Another challenge is the stability of such systems, given known or unknown delays in the communication channel.

Scientist work is not only focused on teleoperation control schemes. The human hand is thought to be the most universal tool. Its universal nature poses many challenges for those designing actuation devices with force-feedback. Rakotondrabe *et al.* [20] proposed a novel method of fitting tie rods on an exoskeleton covering the human hand, which very closely resembles the solution observed in the natural world [2, 3, 11–13, 15, 21–27]. Fingertips are important elements of the human hand. They have also been modified regarding their mechanical structure. Zhang et al. worked on the structure of the fingertip of a manipulator for the human hand [12, 28].

Further in section 1.1 of the paper we are going to introduce what, in our opinion, are the most important papers regarding control schemes and algorithms that have pushed forward telerobotics, from 1966 to the present day.

1.1. Achievements in the Field of the Sensory Teleoperation Devices

Any analysis of researchers' achievements in the field of master-slave systems would show how diversified the systems have become, as their type depends on the control system. This diversity will be discussed briefly below.

In 1966, William R. Ferrel introduced work about master-slave manipulators, where forces were encountered by the remote hand and were transmitted back to the operator. The author discovered that at very great distances there was a transmission delay between an operator's movement and a resulting force. An investigation was made into the effect of long delays and differences in strategy on positioning time with force-feedback alone. Positioning could be accomplished, but delay, coupled with high loop gain, created serious instability [14].

Gunter Niemeyer, in his work [29], discussed problems of telerobotics. Author mentioned about many new potential uses of advanced telerobotic systems that have recently been suggested or explored, such as safety applications or microsurgery. What is important is that this paper studied how the existence of transmission time delays affects the application of advanced robot control schemes for effective force-reflecting telerobotic systems, which would best exploit the presence of the human operator, while making full use of available robot control technology and computing power.

In 1992, Won S. Kim presented two papers [9, 10], 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 control scheme was incorporated into an advanced six degree of freedom force-reflecting telemanipulation system. 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. Third and fourth novel schemes of force-reflecting control enabled 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.

In 1993, Thomas B. Sheridan summarized thirty years of research into dealing with the effects of time delay in the control loop on human teleoperations in space [30]. The author presented experiments which showed the effects of the delay on human performance in task completion, along with demonstrations of predictive displays to help the person overcome the delay.

Dale A. Lawrence's 1993 work involved space applications of telerobots, characterized by significant communication delays between operator commands and resulting robot actions at a remote site [31]. A high degree of telepresence was also desired to enable operators to conduct teleoperation tasks safely.

In 1994, Yasuyoshi Yokokohji [32] presented the analysis and design methods of master-slave teleoperation systems. The primary goal of this paper was to build a superior master-slave system that could provide good maneuverability. Author proposed new control schemes of master-slave manipulators that provide the ideal kinesthetic coupling, such the operator could maneuver the system as though they were directly manipulating the remote object by themselves.

In 1999, Jong Hyeon Park presented an important paper about bilateral teleoperation systems, connected to computer networks such as the Internet [33]. Control schemes have to deal with varying communication time delay. Based on this fact, it was easy for the entire to become unstable due to irregular time delays. In this paper, the author designed a sliding-mode controller for the slave, and an impedance controller for the master. The author proposed a modified sliding-mode controller, in which the nonlinear gain could be set independently of the time delay variation.

Wen-Hong Zhu, in 2000, presented an adaptive motion/force controller which was developed for unilateral or bilateral teleoperation systems [34]. This method could be applied in both position- and rate-control modes, with arbitrary motion or force scaling.

In 2001, Paula Arcara presented a number of control schemes [18, 19], proposed for telemanipulation robotic systems. Because of the intrinsically inconstant and large time delays, due to the communication channel, passivity was largely used in these schemes in order to achieve the stability of the overall teleoperation system.

Craig W. Alexander, in 2001, developed a tuning method which was compared to an adaptive Smith Predictor strategy [35]. The robustness of each method was considered for time-varying plant parameters.

Saghir Mumir's and Wayne J. Book work in 2001, reintroduced wave-based teleoperation from a new point of view [36]. The authors were able to sort out the main disadvantage of this method, which previously relied on the performance deteriorating rapidly with increasing delay. This work focused on the use of a modified Smith Predictor, a Kalman filter, and an energy regulator to improve the performance of a wave-based teleoperator working through the Internet with varying time delay.

The most recent control scheme developed for bilateral teleoperation with force-feedback was published by Ilia G. Polushin in 2015 [4, 37]. This type of algorithm was a modified projection-based force-reflection algorithm, which has been demonstrated to substantially improve stability characteristics of bilateral teleoperators with communication delays. A new type of PBFR algorithm was developed, which solved the aforementioned problem. The new algorithm was based on the idea of separating different frequency bands in the force-reflection signal, and applying the PBFR principle to the low-frequency component, while reflecting the high-frequency component directly.

This is yet another application of force-feedback systems. Another is the interaction and sensory feeling of a virtual environment; a method on which many scientists have been working for years. Researchers have suggested many control schemes for objects that are part of master-slave systems, including passive, predictive, adaptive, and wave-variable control, control with variable structure, or sliding-mode control. The decision as to which of the above would be the best when designing a new master-slave system is crucial, as it will result in either an improvement or a deterioration of the system performance [1–17, 38–40].

1.2. Sensorless Bilateral Teleoperation Systems

So far, domain of sensorless teleoperation belongs to piezoelectric crystals. Piezoelectric crystals can work at the same time as actuator, body and a force sensor, especially, when we are developing devices from a large group of single crystals. An advantage of using piezoelectric crystals as actuators is that we can definitely add their speed and forces, even computed by single crystal. Disadvantages of using this type of crystals are that they use high voltage sources, and while it is important that they are really small, they are also very expensive. Researchers focus not only on control schemes aimed at better stability, but also on the quality of reflecting effect of the environment on actuators.

In 1998, Tadao Takigami introduced a self-sensing actuator for the first time, which was a new concept for intelligent materials, where a single piezoelectric element simultaneously performs as both a sensor and an actuator [28].

In 2006, Yuguo Cui discover that the displacement of a micro-motion worktable driven by a piezo-ceramic actuator could be measured by the self-sensing method in the absence of an independent sensor [41].

In 2007, Wei Tech Ang found that the effective employment of piezoelectric actuators in microscale dynamic trajectory-tracking applications was limited by two factors: the intrinsic hysteretic behavior of piezoelectric ceramic; and structural vibration as a result of the actuator's own mass, stiffness, and damping properties [42].

Yusuke Ishikiriyama and T. Morita, in 2010, presented work about self-sensing control method of piezoelectric actuators that compensate for the hysteresis characteristics by using the linear relationship between the permittivity change and the piezoelectric displacement [43].

Also in 2010, Micky Rakotondrabe focused on the dynamic self-sensing of the motion of piezoelectric actuators [44]. The proposed measurement technique was subsequently used for a closed-loop control. Aiming to obtain a self-sensing 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.

Again in 2011, Micky Rakotondrabe, developed a new micro-gripper dedicated to micromanipulation and micro-assembly tasks [45]. Based on a new actuator, called a thermo-piezoelectric actuator, the micro-gripper presents both high-range and high-positioning resolution.

Finally, Micky Rakotondrabe continue his studies and, in 2015, presented his work about a self-sensing technique, using an actuator as a sensor at the same time [20, 46]. This was possible for most actuators with a physically reversible principle, such as piezoelectric materials.

Sensorless and self-sensing, large appliances are rare, even in scientific literature. There are only couple of paper, rising problem of inverse modelling used in self-sensing control unit of bilateral teleoperators. This work and papers [25, 32, 40, 47–50], addresses this problem.

First paper [48], presents a method for the impedance control of a pneumatic linear actuator for tasks involving contact interaction. The method presented takes advantage of the natural compliance of pneumatic actuators such that a load cell, typically used in impedance control. The central notion of the method is that by departing from a stiff actuation system, low-bandwidth acceleration measurements could be used in lieu of high-bandwidth force measurements.

Second paper [51], presents teleoperated minimally invasive surgery systems, measurement and display of sense of force to the operator was a problem. In this paper, it was proposed a master-slave system for laparoscopic surgery, which can provide force-feedback to the surgeon without using force sensors. Pneumatic cylinders were used as the actuator of the manipulators to achieve this.

Both papers are based on the same control methodology, the impedance control. In [48] control methodology contained an inner loop to control the pressure on two sides of a pneumatic cylinder, while an outer loop enforces an impedance relationship between external forces and motion and commands desired pressures to the inner loop. The inner loop enforces the natural compliance of the pneumatic actuator by controlling both the sum and difference of the pressures on both sides of the pneumatic actuator. In [51], a bilateral dynamic control system was designed using a neural network for acquisition of the inverse dynamics. The obtained inverse dynamics was used as a feedforward controller and to estimate the external force from the differential pressure of the cylinders.

1.3. Scope of Study

So far, the main presented control schemes for bilateral teleoperation systems with force-feedback have some defects. These defects mean the use a large number of sensors were required, mediating between the environment and the bodies of the slave manipulator, in rotary joints. A situation in which the environment affects one degree of freedom, in accordance with that degree of freedom, is relatively simple by using a single sensor. However, where the design of the manipulator depends on many degrees of freedom, and moves in the three-dimensional space, use of a single or multiple sensors could be considered as expensive, or not adequate for the proper operation of such a system.

This paper presents a novel approach for designing a control scheme for a master-slave system with force feed-back. The difference between figures presenting sensor methods thus far is that, in the case of the proposed control scheme, there are no sensors mediating between the manipulator body and the environment, relative to paper [1–19]. The same thing can be noticed in self-sensing piezo-ceramic microcontrollers used for micromanipulation and in [2, 20, 28, 32, 41, 43–46]. The only sensors used in the whole system are position encoders and pressure sensors. Where a simple pneumatic manipulator is an introduction to the work on the car cranes, which are actually much bigger than devices in the presented literature.

According to this project, operator needs to feel the crane load, but also the feeling of a contact is required. Contact between the object of environment must be realized in the way that, the system will push back the operator, in the contact situation with unmovable object. Introduction to work on much bigger devices, means consideration of disadvantages like long hydraulic pipes, which are also included in the presented test-stand. The problem of high friction values and many other, which will occur during further work, have to be overcome during preliminary work on the test-stand.

Inverse model of the manipulator structure used in the control unit corresponds to the manipulator operation without any environmental impact on the slave subsystem. Based on this fact it is possible to obtain relatively accurate information about the environmental impact on the specific degree of freedom of the slave manipulator. This important feature eliminates the need to use a sensor (susceptible component) between the body of the manipulator and the environment, or between the actuator and the manipulator body.

An important feature of this approach on the design of the control system is that the value of the impact of the environment is transmitted to a specific master manipulator degree of freedom, as a response from the equivalent degree of freedom in the slave manipulator, but without using geometrical relationships resulting from the construction of the manipulator. Difference between impedance control [49, 52], in this paper system is that, the system is not controlling the pressure inside the actuator chamber, which measured pressure is being subtracted by the estimated pressure. This estimated pressure, is calculated by the inverse model of subsystem Slave.

2. Problems and Modeling of Self-sensing System I Bilateral Teleoperation

This section of work, discusses theoretical problems of teleoperation with force-feedback.

First important problem are the delays in the communication channel. The delays are the main feature causing the instability of such a system. Many designed control schemes focus on maintaining the stability of the telemanipulation system, see [1–19] for further details.

Second issue of described systems, is the transmittance of object felt in the force-feedback channel by the operator of subsystem Master, during free motion of the Slave subsystem. Where free motion of Slave manipulator is understood as a motion without interaction between the Slave subsystem and the environment.

Third and last problem, that will be discussed is the transmittance felt in the force-feedback channel by the operator of subsystem Master, during interaction between the Slave manipulator and the environment. This is a key factor, which tells the operator, how well he can feel the environmental impact on the Slave manipulator joint.

There are also many other characteristic features, which describe the robustness, stability and optimal control of telemanipulator systems. The perfect example is an inertia, a damping, a tracking, a stiffness and a mass felt in the force-feedback channel. Authors of [18, 19], have described, that the ideal telemanipulator should be stable for any value of time delay in the communication channel, present an inertia as low as possible, achieve zero tracking error, display the same stiffness at the master side as the one perceived in the interaction at the slave side, present no position drift during contact between Slave manipulator and the environment object.

2.1. Self-sensing Sensorless Estimation Method in Force Feedback Telemanipulation, 1-DOF Ideal Example

The remotely controlled system consists of two subsystems – the Master subsystem and the Slave subsystem. Both subsystems, the Master (a), and the Slave (b), are presented in Fig. 1, are a simple rigid objects described by their inertia.

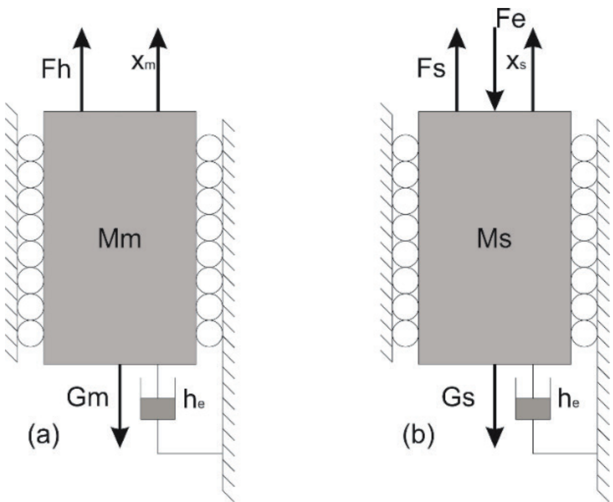

Fig. 1. Graphical presentation of models: master subsystem (a), the slave subsystem (b)

These manipulator bodies move in an environment described by the dissipative element h_e. The damper represents a center of air. The bodies of the manipulators move without the 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 two 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.

2.2. Ideal Master-Slave System Transmittance Analysis

Executive 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, which is described by the damping parameter h_e. Slave manipulator is described by its mass – M_s, gravity force G_s, trajectory – x_s, control force F_s, which is generated by the actuator and the environmental impact – by force F_e.

The transfer function B_i, which describes dynamics of manipulators, can be presented as an equation (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. Further designation used in this work is included in Tab. 1.

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

In Fig. 2, system senses the environmental force impact, by the force sensor and sends the value of force, back to the Master manipulator in the communication channel F_{es}. In presented work, system do not measure environmental force impact, but estimates its value based on the control signals of the slave controller and current Slave manipulator position. Modified structure of the telemanipulation system is presented in Fig. 3.

In presented method system has an additional block in the communication channel. The estimation block, calculates the force of environmental impact based on the force value computed by the model of the Slave subsystem. Force-feedback estimation

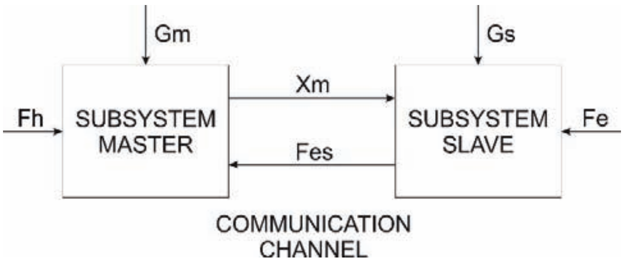

Fig. 2. Block diagram of standard sensor method

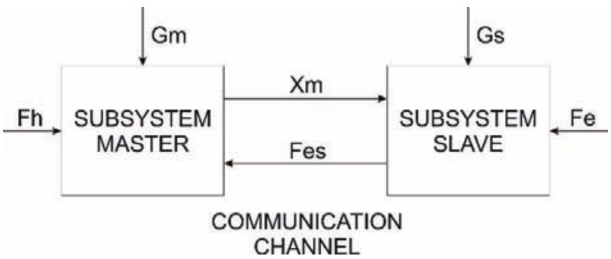

Fig. 3. Block diagram of the presented method with the force-feedback estimation block

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

Designation	Description
F_h	Force applied by man to the body of Master manipulator
F_e	Environmental force impact on the slave manipulator
F_s	Control force on the Slave side, which is generated by the actuator
F_{es}	Estimated value of the force-feedback, in the communication channel
F_{sm}	The estimated value of the force generated by the drive, during the free motion of manipulator a slave.
G_m	Gravity force attached to the Master manipulator
G_s	Gravity force attached to the Slave manipulator
B_m	Transfer function, which describes dynamics of the Master manipulator
B_s	Transfer function, which describes dynamics of the Slave manipulator
$e(s)$	Position error in control unit of the Slave manipulator
$K(s)$	Transfer function, which describes regulator of Slave manipulator position
M_s	Slave manipulator inertia
M_m	Master manipulator inertia
x_m	Master manipulator position
x_s	Slave manipulator position

block, subtracts measured force of the drive, from estimated by model in free motion. Modified system is described in detail in Fig. 4.

One of the main problem of methods, which are using force sensors and rotary joints is that, the control unit need a huge amount of force sensors placed

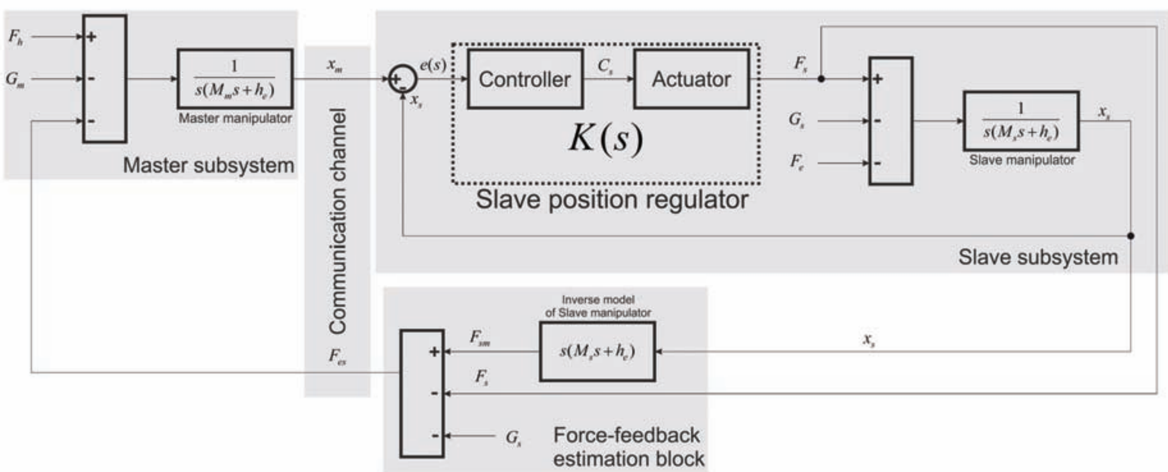

Fig. 4. Block diagram of system in details, used for the proofs and analysis

on the manipulator arm. This feature is crucial to deliver correct value of environmental torque impact in each joint, using standard sensor control scheme for teleoperation. Presented method delivers values of environmental force impact on the slave manipulator to the operator, which is measured in the drive track in each joint of the Slave manipulator independently.

In the paper an analysis of the proposed method is presented. In results the system, based on the presented method of estimation in the force-feedback channel, will send to the Master manipulator zero value of force, during free-motion of Slave manipulator.

First characteristic transmittance, which describes 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 as equation (2):

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

First step in finding the slave subsystem closed-loop and the inverse model transmittance, is reducing the Slave subsystem transmittance – see Fig. 4, to a simple transfer function. This transfer function will be described by a relation of two signals x_m, which is the position of Master, sent to Slave and the x_s, which is the position of Slave. The transmittance is presented as equation (3):

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

Equation (3) describes the closed-loop system of the Slave manipulator, including transfer function of the position controller $K(s)$. The controller transfer function is unknown for the transmittance analysis, because it is possible to use many structures of position regulators and it won't change presented method result.

In the second step, the slave subsystem closed-loop transfer function is determined as (3). The Second transmittance, including the inverse model of force-feedback estimation block and the closed-loop of slave subsystem, is defined by the ratio of the estimated value of the force generated by the drive, during the free motion of the Slave manipulator – named F_{sm} and the Master position – x_m. Presented in equation (4):

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

Equation (4) describes one of the characteristic transfer functions, the function that is responsible for reducing the force in a force-feedback communication channel.

Third step requires finding the transmittance of closed-loop Slave system, which senses the control signal F_s from the regulator block $K(s)$ output. 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 like it is presented in the third part of this paper, an air pressure. To find this transfer function, it is required to find a solution of two equations presented as (5):

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

where $e(s)$ – Slave subsystem position error, described as $e(s) = x_m(s) - x_s(s)$. Looking for a solution of the equations (5) by ratio of $F(s)/x_m(s)$, we get equation (6):

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

exactly the same as transmittance (4). This means that subsystem Slave during free motion task, sends zero value in the force-feedback communication channel. This is confirmed by the transmittance difference 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 such a system, this situation is really comfortable, but requires very accurate inverse mathematical model of subsystem slave.

It is important to show, that the subsystem slave, which is under influence of the environmental force, sends to the operator exactly the force of the environmental impact.

In the second part of transmittance analysis (4) and (6), external forces are taken in to account. These forces were omitted during first analysis. We get two new equations (8) and (9), which describes Slave subsystem in the Fig. 4:

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

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

Subtracting equations (8) and (9), obtain equation (10):

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

After simplifying equation (10) we get (11):

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

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

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

As it is seen, if we are able to build a high accurate mathematical model of Slave subsystem, it is possible to transmit the value of the environmental impact exactly, to the operator by using the presented method. Note, however, that getting a model that exactly corresponds to the actual object, is in practice very difficult or even impossible, so the value of its environment in a force-feedback presented system will strongly depend on the accuracy of this model.

2.3. Ideal Master-Slave Stability Analysis

Theoretical stability analysis of presented method, according to the ideal system presented in Fig. 4 is simple. The force-feedback communication channel, delivers to the operator, information about environmental impact on the Slave manipulator. In the ideal situation, inverse model of Slave subsystem is subtracting only some value from measured force signal. If the inverse model is stable and the delay in the communication channel is negligible, there is no need of stability analysis, because the operators force F_h, is applied to the body of manipulator, which is a second order transfer function. But when high value of delay T appears in the communication channel, system will send to the operator, value of the force-feedback with double delay T and the operator will be the main cause of the instability of this system, when he will be unaware of the delay in the communication channel (Exceptions are variable delays in the communication channel and different constant delays in different ways of communication channel, but this work focuses only on system where the delay is considered as negligible). The double delay in force-feedback communication channel comes from the problem of telemanipulation bilateralism. Systems send information in both directions with delays. So the force-feedback communication channel will be described as an equation (13):

$$F_{es}(s) = e^{-2sT}F_e, \qquad (13)$$

where T is the value of delay in seconds, only in one direction, and in one communication channel.

At this point, appears a serious problem. What if, the model is slightly different than Slave subsystem? The system will be described quite differently than it is presented in this work, but this problem will be discussed in another work.

3. The Experiment

3.1. Mechanical Structure of the Test-Stand

The mechanical features of a slave and a master subsystem are completely identical. The exoskeleton subsystem master was attached to the operator's elbow. Hence, it was not necessary to do the calculations of pressure in the feedback resulting from differences in the mass and dimensions of the master and the slave. The subsystem master was mounted on a strong and heavy table. The experimental setup is presented in Fig. 5.

The manipulator arm with its drive system which was taken into account in the mathematical inverse model of pressure in chambers. There is a stationary base plate, which is fixed to the table. The bending actuator and its extension bend the manipulator arm. The straightening actuator and its extension straighten the manipulator arm.

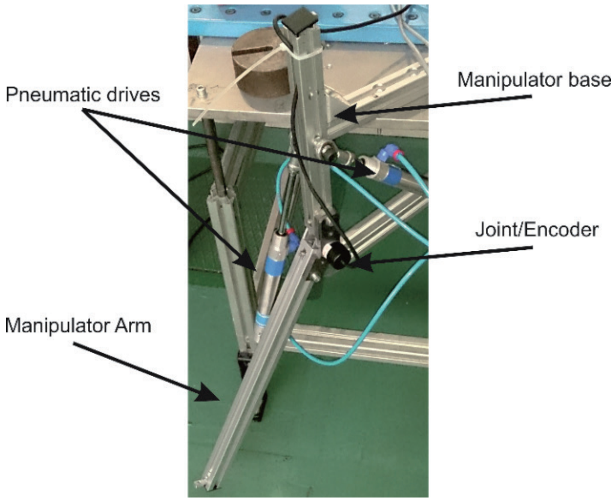

Fig. 5. Slave Manipulator

As can be seen, the radius at which the actuator computes motion is not constant. This radius depends on the rotated position of the manipulator arm. This important feature makes the subsystem slave a nonlinear object. This feature caused problems in the control and modeling of the subsystem slave. Mounting pneumatic drives in this way is not accidental. Using two drives, affects the symmetry of the surface of the piston, which, as it turned out, considerably improved the quality and stability of the entire subsystem slave. The manipulator body is made of an aluminum alloy, while the entire structure was permanently mounted on the table.

Two types of signals are used in the system. Output signals are analog signals for pressure measurement, and input/output discrete signals for the encoders and valves. Encoders that were used to build the test-stand had a number of pulses equal to 500 per revolution. The pressure gauge used to measure pressure in the system had a maximum measurement value of 10 bar, proportionally sensing the pressure as 1 to 10 V. Referring to the equations from part 2 of paper, those variables can be given a new designation that are more characteristic of pneumatics.

As you can see in Fig. 6, there are three control signals V_1, V_2 and SD (C_s in Fig. 4). They are summarized in Tab. 2.

P_s is an analog pressure sensor for a slave subsystem. Only one pressure sensor was used in the system, which had the task to bring a test-stand solution

Tab. 2 Signals in pneumatic control scheme – slave

Theoretical Designation	Pneumatic Designation	Description
C_s	$\begin{bmatrix} V_1 \\ V_2 \\ SD \end{bmatrix}$	– discrete signal controlling left coil of the valve – discrete signal controlling right coil of the valve – PWM used to control the throttle
F_s	P_s	– analogue pressure sensor signal

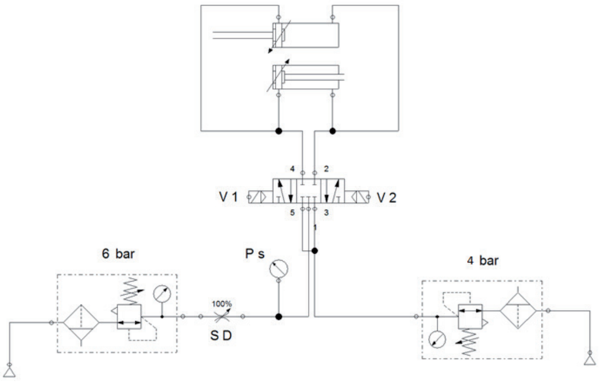

Fig. 6. Pneumatic scheme of slave

closer to a bulky lifting equipment, like a car cranes. Usually it is not possible to modify those structures on a large scale. Theoretically, the control signals correspond exactly to the same control structure. Namely, it is a fact that the previously discussed force was passed in the channels of communication in the theoretical model from Fig. 4. In the research bench is the pressure in the piston chamber at a given moment in the system. In the case of a master subsystem it was easy to use a pressure control valve (see Fig. 7), which controls the air pressure on the basis of the set value. Then the pressure will only reach destined piston chambers using on/off valves V_4 and V_5.

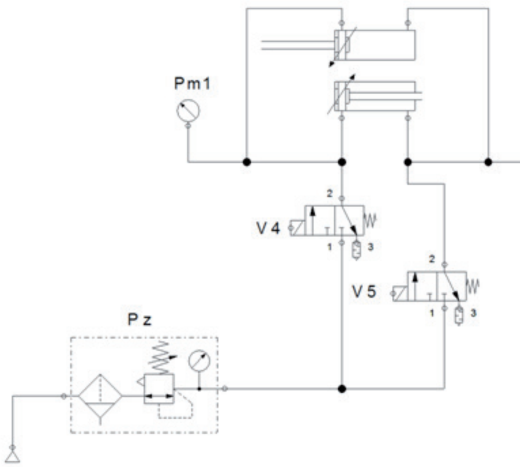

Fig. 7. Pneumatic scheme of Master

Use of P_z, the pressure control valve, in this manner increases the cost, and makes it difficult to build the entire system, but it reduces the effect of a stepped pressure rise when only 3/2 switching valves are administered, which are controlled by solenoids.

At the initial stage, one could say that the greatest impact on the results of the experiment will be the slave subsystem, it was required to make sure that its behavior is optimal. An important feature was also the design of the actuators. The cylinders, as shown in Fig. 5 and Fig. 6, are mounted in such a way, that their effective piston areas are symmetrical, resulting in a significant improvement in the stability of the entire system, as shown in Fig. 8.

The arrangement of cylinders was not the only modification; a throttle servo mechanism was also used, which controls the amount of an air flow based on the value of the error; the effect of both modifications is compared in Fig. 8. It can be seen that the improvement of the quality of work is relatively large. A system without identical piston areas and a throttle servo mechanism could not be considered to work properly, while with the introduction of modifications the system becomes stable, and the quality of the motion shows a significant improvement. Characteristics shown in Fig. 8 illustrate perfectly how this change affected the improvement of slave subsystem motion tracking was improved. A 25% difference in the surface of the pistons leads to significant oscillation and instability. This meant that the system was not fit for further work on it.

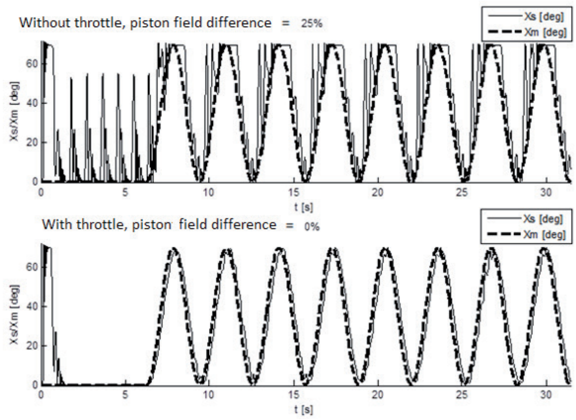

Fig. 8. Behavior of the system without and with throttle

The introduction of the symmetry of the surface of the piston has other very important advantages: the system generates similar forces in both directions, at the same time. The necessity of conversion in the control pressure forces was thus omitted. The modifier that allows the improvement in the work object slave manipulator arm is also a servo throttle, and its absence also resulted in significant oscillations and instability of the system. The throttle led to the termination of system oscillations and to generating a trajectory, in a manner very similar to the reference even using simple PID control. The PID controller parameters were selected by an operator during system operation.

3.2. Modeling of Pressure in the Actuator Chamber

Based on Equations (1) to (12) from part II of the paper, it is possible to build a model of a subsystem slave, which describes the dynamics of the system, and also shows how the pressure is estimated, based on the input signal of the model and on the slave subsystem position.

First of all, there is a model of the geometrical structure of slave subsystem, which is required. The model is actually an inverse model of nonlinear manipulator arm. Based on the manipulator arm, a geometrical and dynamic model of the slave and master subsystem was built, as shown in Fig. 9.

The angles of mechanical structure are changing iteratively. The geometrical model of rotating arm is

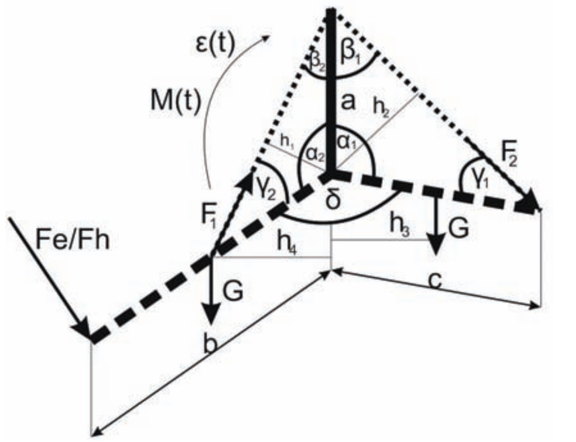

Fig. 9. The geometrical relationships in manipulator structures considered in inverse modelling

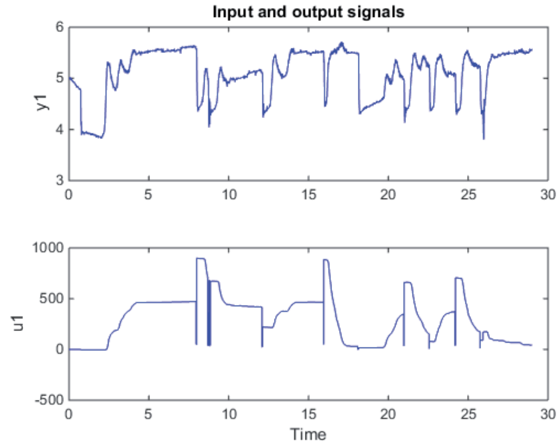

Fig. 10. Base measurement for identification of the model pressure on the test bench

dependent on the dimensions of actuators. The dimensions of each actuator cause movement of the entire manipulator arm. To build a model which will behave exactly like the one in Fig. 5, requires the use of geometrical relationships among actuator, base, and rotational arm of the manipulator, as shown in Fig 9.

Model from Fig. 9 describe the estimated pressure in free motion, in the time domain by equation (14):

$$P_{est}(t) = \frac{G_2 esin(\beta_2(t)) - G_1\frac{d}{2}\sin(\beta_1(t)) - \frac{1}{3}(m_1c^2 + 4m_2b^2)\varepsilon(t)}{\left(A_2 bcos\left(\frac{\pi}{2} - \gamma_2\right) - A_1 bsin(\gamma_1)\right)}, \tag{14}$$

where A_1 and A_2 are the areas of pistons – first and second actuator, ε(t) is the angular acceleration of the manipulator arm, G_1 and G_2 are the gravity forces applied to the body of manipulator. Rest variable values are angles and radiuses used for derive the equation (14).

As it turned out during tests, simple geometric and mechanical model was not enough to properly estimate pressure. This model was incorporated to structure of nonlinear autoregressive model with exogenous input – NLARX. The nonlinear part of model NLARX was based on binary tree. This model has estimated relatively good the pressure, relative to the simple equation (14).

3.3. Inverse Dynamics Model on NLARX Structure

All the components of the slave responsible for initiating motion were taken into account while modeling, included valves and the mechanical structure of the manipulator. When the test-stand had been completed, the setting signals, the position, and pressure signals in the actuator chamber were recorded, as shown in Fig. 10.

The upper run y_1 shows pressure changes during the system operation. The lower run, as presented in Fig. 10, shows a certain cluster of setting signals, based on Equation (15):

$$u_1 = (X_s V_1 + X_s V_2 + SD * X_s), \tag{15}$$

where V_1 and V_2 are discrete signals of opening of valve 5/3, is the percentage of valve lift of the controlled throttle, X_s is the current position of the slave, and y_1 is the measured pressure.

The fundamental measurement, which shows that one setting signal was generated from several signals. It turned out during tests that this signal was more efficient in terms of modeling than providing several signals individually.

An attempt was made to identify many models with the runs shown in Fig. 10. However, it was difficult to find a model that would provide a minimum fit of 20%, compared to the reference runs. According to a criterion based on the function FIT (Fit curve or surface to data function) from Matlab and defined with Equation (16):

$$FIT = 100\% \left(\frac{y_h - y}{y - \hat{y}}\right), \tag{16}$$

where y_h is the output from the identified model, ŷ is the average value of the real run, and y in the model is the measurement of pressure. The only model that had the potential of being relatively accurate was NLARX – pressure run and NLARX model response presented in Fig. 11.

NLARX can represent pressure changes in the real system relatively well and, according to the FIT criterion, it reaches 78% of probability. The result was so good that it had to be double-checked whether or not it was a coincidence. Therefore, another pressure measurement was made for the same trajectory and it was checked how the model would behave, given

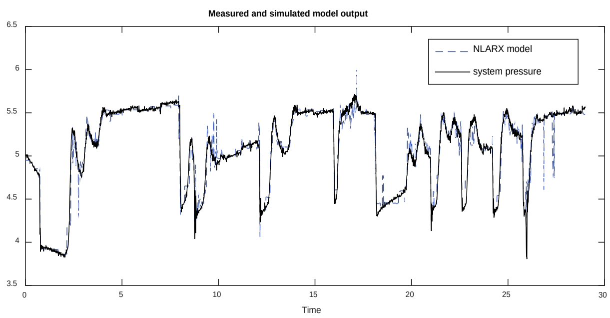

Fig. 11. NLARX model response against the measured signal

the same setting signals. The run turned out to be almost the same as that shown in Fig. 11, and it reached a very similar value of 77.5% of similarity between the reference and modeled pressure changes.

Based on all features, which were described in section 3 so far, slave side controller was modified to the form shown in Fig 12.

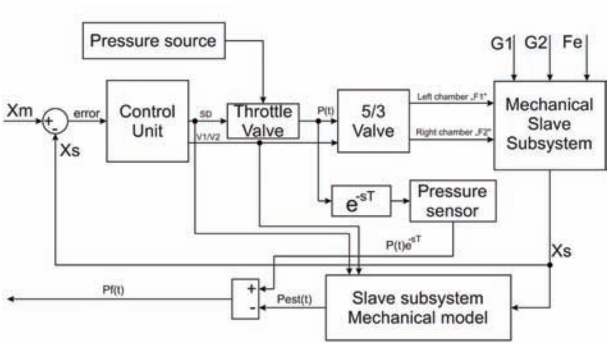

Fig. 12. Subsystem Salve control unit including delay in the pneumatic tubes

As it is presented, slave subsystem mechanical model used more signals, than it was initially established. This model used inputs and outputs of the slave device. The problem of long pneumatic tubes occured during analysis. But as it turn out operator could barely feel the delay of pressure feedback on the Master Manipulator, even if the delay was relatively large and it was 0.5 seconds.

3.4. Experimental Results

Having identified the model of the slave subsystem, tests were conducted to verify the operation of the whole system. The aim of the first measurement was to check how the system would behave, given no interaction with the environment. The only interaction of the environment which occurs for the nonlinear manipulator arm is gravity and resistance to motion, and in this particular case, the friction and resistance of air surrounding the manipulator. However, even these component data were modeled within the structure of model NLARX. Owing to this, such data can be considered as negligible when conducting certain runs by the slave system of the manipulator, as they exert the same influence both on the real object and on the model. Some interesting runs of the first experiment are presented in Fig. 13.

The aim of the second experiment was to check if the system would show the maximum pressure at the moment when it would encounter an object it would not be able to move. The results of the experiment are shown in Fig. 14.

The contact phase can be seen in the upper and lower runs. The control system precisely mapped the maximum pressure of 2 bar. The maximum pressure of 2 bar in force feedback is the effective pressure, resulting from using the control method that relies on pressure changes in the system. The maximum pressure in the system is 6 bar. However, it is counteracted by the pressure of 4 bar, and the whole system stiffens. The value of 2 bar means that the system was able to

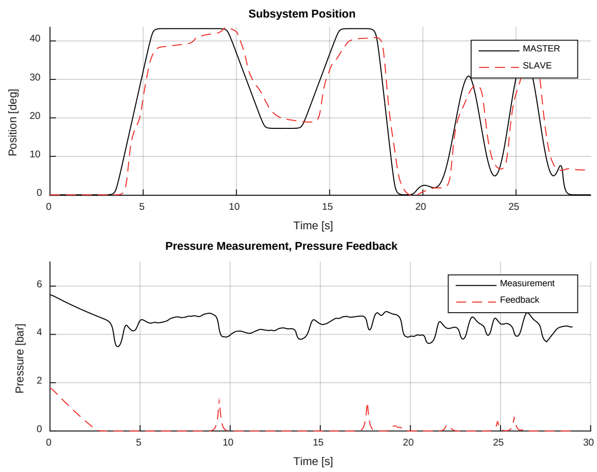

Fig. 13. Master-slave system test bench; First test

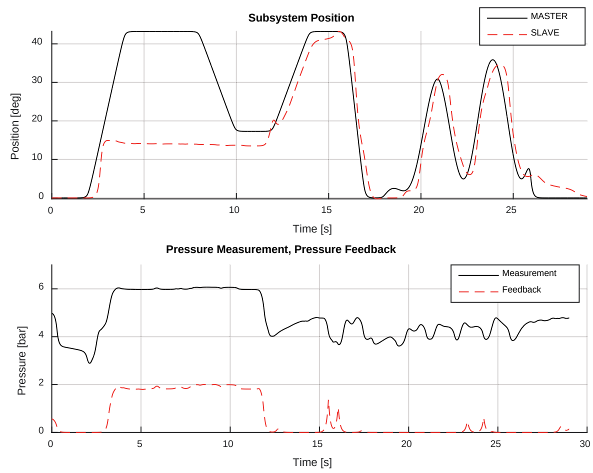

Fig. 14. Master-slave system test bench; Second test

transmit adequate information to the feedback with a relatively large time delay of 0.5 s. This is due to the compressibility of the medium in the system, and is not the fault of the control system whose clocking frequency was 10 kHz.

Third and last test was focused on goal, if the system was able to feel the load of inertia, which was attached to the slave manipulator arm. Run can be seen in Fig. 15.

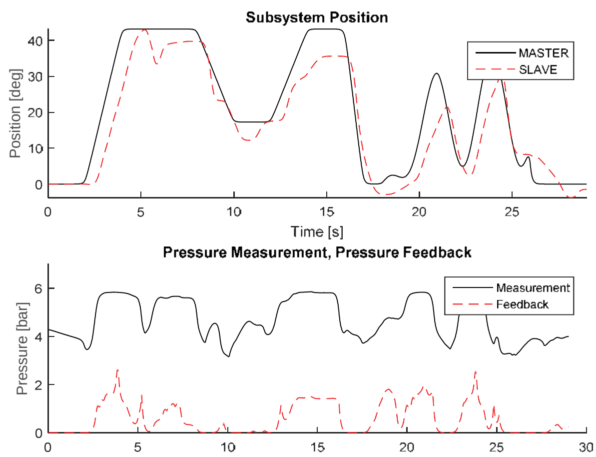

Fig. 15. Master-slave system test bench; Third test

The estimated pressure, this time was seriously distorted, but around 15 second of lower run at steady state it delivered the information with only 5% error to the expected value. The main cause of distorted pressure feedback was simple PID controller and the disturbed position tracking ability with high change of manipulator arm inertia. Imperfect model also had an impact on the distortion of the value in the force-feedback communication channel. In the future, the ability of position tracking will be improved, but on different hydraulic device.

4. Conclusion

The aim of the experiment was to verify whether or not the operator is able to feel the effect of environment on the slave, using a pneumatic drives and relatively inexpensive control systems using an inverse dynamics model and based on a nonlinear object. It is naturally possible to confirm the assumption. However, it is biased with a relatively large error depending on the similarity between the model and the real object. A typical PID controller was used for position control, due to its simple implementation. It was also important because of the low computing power of the system controller, whose computing capacity was focused on the mathematical model that simulated pressure in the drive system of the slave. This work did not focus on position tracking ability, but on the self-sensing pressure estimation in the force-feedback communication channel.

Concerning the contact phenomenon, the presented system transfers stimuli from the outside environment until it attempts to grip, or until it comes into contact with the environment. When it attempts to grip, a problem arises, as the system is controlled with position error only, and does not have any deformable elements. This means that the object will be gripped with the maximum force, and this value will be sent over to the master; i.e. the operator. It can be dealt with by tuning the system to accommodate lower effective pressure. Consequently, the force with which the system will press on an object can be regulated. However, at this point, another drawback of the system is manifested. Even the smallest change in pressure will result in having to change the mathematical model that simulates pressure. This adds the additional challenge of having to find the right model, which is both difficult and time-consuming.

In the future, the ability of position tracking will be improved, but on a different hydraulic device. Also it is planned to close the self-sensing method inside the controller, without use of external sensors like the pressure sensor used in this paper.

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AUTHORS

Mateusz Saków* – Institute of Mechanical Technology, Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University, Szczecin, 70-310 Piastów 19, Poland.
E-mail: mateusz.sakow@zut.edu.pl.

Karol Miądlicki – Institute of Mechanical Technology, Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University, Szczecin, 70-310 Piastów 19, Poland.
E-mail: karol.miadlicki@zut.edu.pl.

Arkadiusz Parus – Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University, Szczecin, 70-310 Piastów 19. Poland.
E-mail: arkadiusz.parus@zut.edu.pl.

*Corresponding author

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