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Load Self-Sensing Control Scheme for Telemanipulation - Part 1: Theory

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Abstract: The paper presents a novel approach to a control design of bilateral teleoperation systems with force-feedback dedicated only for a sensor-less weight sensing. 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 was based on a dynamics inverse model. The model was used to subtract a value of force in the force-feedback communication channel that the system might generate during free-motion. A substantial part of the paper, is focused on a development of a mathematical model covering phenomena occurring in the investigated control scheme.

Keywords: telemanipulation, force-feedback, inverse modeling, telerobotics, remote control

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. The applications of master-slave systems are widespread, including performing tasks in environments hostile to man as: (1) contaminated sites; (2) in the depths of oceans and seas; (3) radioactive interiors of nuclear power plants; and even other applications like (4) medical rehabilitation.

Most of master-slave systems are unilateral [11–16, 21, 28, 30, 32, 36–38]; i.e. a device that is being controlled (slave) should behave exactly as the device that controls it (master). However, as research continued, it was noticed that the operator, that enters into interaction with the master subsystem/manipulator should be able to feel the haptic effect of the environment on the slave subsystem side.

The haptic effect problem posed significant challenges in its practical application, due to large distances and the inevitable time delay [1–5, 9, 10, 17, 18, 20–22, 26–31, 33, 39, 45, 46]. 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 is a time delay, which 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.

So far, sensor-less bilateral teleoperation solutions are mainly based on 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. For the first time in 1998, Tadao Takigimi et al.; the authors of the paper, introduced a self-sensing actuator which was a new concept for intelligent materials, where a single piezoelectric element simultaneously performs as a sensor and an actuator at the same time [40]. In 2006, Yuguo Cui, discovered 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 [44]. Finally in 2007, Wei Tech Ang, found that the effective employment of piezoelectric actuators in micro scale dynamic trajectory-tracking applications was limited by two factors: (1) the intrinsic hysteretic behavior of piezoelectric ceramic; and (2) structural vibration as a result of the actuator's own mass, stiffness, and damping properties [41]. Then, Yusuke Ishikiriyama and T. Morita in 2010, published a paper 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 [7]. Also in 2010, Micky Rakotondrabe focused his research on the dynamic self-sensing of the motion of piezoelectric actuators [24]. 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 [23]. Based on a new actuator, called a thermo-piezoelectric actuator, the micro-gripper presented high-range and high-positioning resolution. Finally, Micky Rakotondrabe continue his studies and in 2015, presented his work about a self-sensing technique, using

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an actuator as a sensor at the same time [24, 32]. This was possible for most actuators with a physically reversible principle, such as piezoelectric materials.

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 mediating between the environment and the bodies of the slave manipulator, especially 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 single or multiple sensors could be considered as expensive, or not adequate for the proper operation of such a system.

The paper presents an approach to design of a control scheme for a master-slave system with force-feedback. The difference between 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 papers [6, 19, 34, 35, 42, 43]. The same thing can be noticed in self-sensing and piezo-ceramic micromanipulators used for micromanipulation an in impedance control methods [7, 8, 23–25, 40, 41, 44]. The only sensors used in whole system are position encoders and pressure sensors. Whole manipulator body is considered as perfectly rigid body. In this paper, the operator needs to feel the manipulator load, but also a haptic effect of a contact is required. Thus, a sensor-less method of force-feedback and its analysis estimation is presented in the part 1 of the paper. The method analysis was carried out on a simple 1-DoF object describing a manipulator. This approach was used to make the transfer function analysis easier to understand for a reader.

2. Self-Sensing Control Scheme for Teleoperation with Perfectly Rigid Bodies

The presented sensor-less control scheme for bilateral teleoperation consists 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 the Fig. 1.

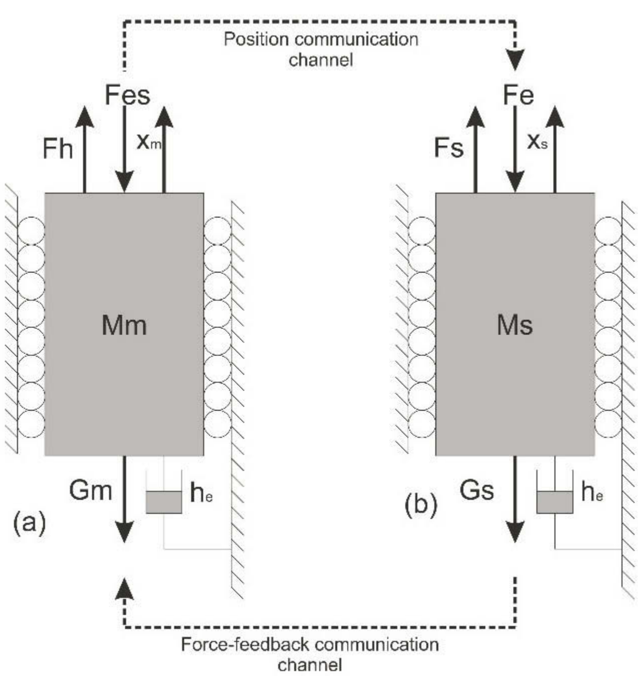

Fig. 1. Graphical presentation of models: the Master subsystem (a), the Slave subsystem (b)
Rys. 1. Graficzna prezentacji modeli: (a) podsystem Master, (b) podsystem Slave

These manipulator bodies move in an environment described by the dissipative element h_e. The damper represents any type of motion resistance. The bodies of the manipulators move without the friction between them, and the world frame. Master subsystem acts as a motion scanner which sends information about its own position x_m to 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 the Master manipulator. Last force applied to the body of Master manipulator is F_{es} which is transferred in communication channel from Slave subsystem. For theoretical analysis transmittance of Master subsystem actuator, resisting operators motion was not considered.

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. Slave manipulator is described by its mass – M_s, gravity force G_s, position – x_s, control force F_S (theoretically including Slave actuator) that is generated by the actuator, and the environmental impact – by force F_e. The transfer function B_i that describes dynamics of both manipulators, can be presented as the equation (1):

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

where i – index, index m for Master subsystem, index s for Slave subsystem, s – Laplace operator, M_i – mass.

3. Telemanipulation control schemes

In the paper, system do not measure environmental force impact, but it 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. 2.

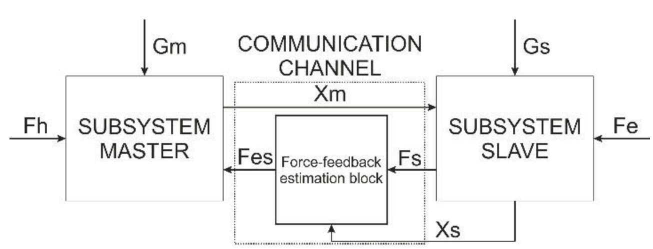

Fig. 2. Block diagram of the presented method with the force-feedback estimation block
Rys. 2. Prezentowany schemat blokowy automatyzacji z blokiem estymacji w kanale siłowego sprzężenia zwrotnego

In the Figure 2, system has an additional block. The estimation block, 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 that estimated by the model in free motion. This measured force could be a hydraulic pressure, a voltage or like it is presented in this paper – a pneumatic air pressure. Modified system is described in details in Fig. 3.

The primary problem of methods using force sensors and rotary joints is that, that the control unit needs a large amount of the force sensors placed on the manipulator arm. This feature is crucial to deliver correct value of environmental torque impact in each rotary joint. In this paper, the method computes

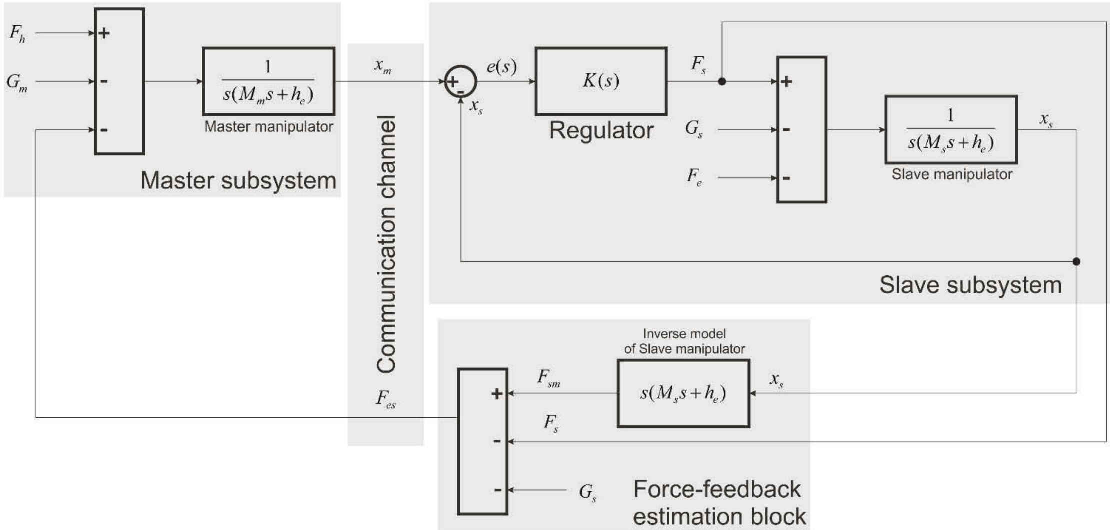

Fig. 3. Block diagram of system in details that was used for the analysis
Rys. 3. Szczegółowy schemat blokowy automatyzacji wykorzystany do analizy matematycznej

value 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. Presented system requires as many sensors of current, voltage or pressure, as many dimensions of freedom are included in the Slave manipulator structure. Rotary or linear joints do not make difference for presented method of estimation environmental forces, on each joint, in the force-feedback communication channel. In the result the system, based on the presented method of estimation in the force-feedback channel (equipped with an ideal model), will send to the Master manipulator zero value of force, during free motion of Slave manipulator. This conclusion will find its proof in the next section of the paper.

4. Theoretical system analysis

To investigate the effectiveness of presented method it is required to find the slave subsystem closed-loop and the inverse model transmittances, by reducing the Slave subsystem transmittance (Fig. 3) to a simple transfer function. First transfer function describes the relation of two signals x_m, which is the position of Master, send to Slave and the x_s, which is position of the Slave manipulator. The transmittance x_s/x_m is presented as follows (2):

$$\frac{x_s(s)}{x_m(s)} = \frac{K(s)}{(M_s s + h_e)s + K(s)}. \tag{2}$$

Equation (2) 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 controllers like simple proportional P, PI or even PID. Different linear controller structure would not change presented method result.

In a continuation of transmittance analysis, the slave subsystem closed-loop transfer function is determined as (2). The Second transmittance, including the inverse model of force-feedback estimation block and the closed-loop of slave subsystem, is defined by a 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, transmittance F_{sm}/x_m is presented by the equation (3):

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

Equation (3) describes one of two, characteristic transfer functions, the function that is responsible for reducing the value of force in a force-feedback communication channel. The force in the communication channel of manipulator system using rotary joints without additional force-feedback estimation block, sends to the operator and Master subsystem a value of force used to achieve the desired configuration of Slave manipulator. This force will depend on actual position of each joints, and also acceleration and velocity, including inertia of individual bodies and motion resistance. This feature appears only during free-motion condition.

Next step, requires finding the transmittance of closed-loop Slave system, which senses the control signal F_s from the controller's 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 a pneumatic air pressure. To find this transfer function, it is required to find a solution of two equations presented as (4):

$$\begin{cases} F_s = K(s)e(s) \\ x_s = \dfrac{F_s}{(M_s s + h_e)s}, \end{cases} \tag{4}$$

where $e(s)$ is a Slave subsystem position error, described as $e(s) = x_m(s) - x_s(s)$. Looking for a solution of the equations (4) by a ratio of $F_s(s)/x_m(s)$, we obtain an equation (5):

$$\frac{F_s(s)}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}, \tag{5}$$

exactly the same as transmittance (4). This means that subsystem Slave during free-motion in remote environment, calculates zero value in the force-feedback communication channel. This is confirmed by the transmittance difference, which is represented as force-feedback estimation block in the Fig. 3, and by the equation (6):

$$F_{es} = \frac{F_s(s)}{x_m(s)} - \frac{F_{sm}(s)}{x_m(s)} = 0. \tag{6}$$

For the operator of a system, which uses presented method, this situation is comfortable, but requires very accurate dynamics inverse model of Slave subsystem. It is important to show, that the slave subsystem which is under influence of the environmental force, sends to the operator exactly the force of the environmental impact. Of course, in a case of theoretical analysis of ideal system presented in the Fig. 3.

The force-feedback transparency analysis, requires external forces to be taken in to account. This forces are included in equations (3) and (5). Two new equations are obtained (7) and (8), which describes the Slave subsystem in the Fig. 3, including external forces:

$$\frac{F_{sm}(s) - G_s}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}, \tag{7}$$

$$\frac{F_s(s) - G_s - F_e}{x_m(s)} = \frac{K(s)(M_s s + h_e)s}{(M_s s + h_e)s + K(s)}. \tag{8}$$

Subtracting equations (7) and (8) and after simplifying them, we obtain the equation (9):

$$F_s(s) - F_{sm}(s) = F_e(s), \tag{9}$$

where the difference $F_s(s) - F_{sm}(s)$ according to the control scheme of Fig. 3, corresponds to the signal of force-feedback communication channel F_{es}, presented as the equation (10):

$$F_{es} = F_e. \tag{10}$$

5. Conclusion

This paper is a part of the theory proof, that if it is possible to use a high accurate mathematical model of the Slave subsystem, it is possible to transmit the value of the environmental force impact, to the operator by using the presented method. Note, however, that getting a model that exactly corresponding 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 by using presented method or system, strongly depends on the accuracy of this model.

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References

1. Ben-Dov D., Salcudean S.E., *A force-controlled pneumatic actuator for use in teleoperation masters*, [in:] Proceedings of 1993 IEEE International Conference on Robotics and Automation, 938–943,
DOI: 10.1109/ROBOT.1993.292264.
2. Ferrell W.R., *Delayed Force Feedback*, “Human Factors: The Journal of the Human Factors and Ergonomics Society”, Vol. 8, No. 5, 1966, 449–455,
DOI: 10.1177/001872086600800509.
3. Guerriero B., Book W., *Haptic Feedback Applied to Pneumatic Walking*, ASME 2008 Dynamic Systems and Control Conference, American Society of Mechanical Engineers, 591–597,
DOI: 10.1115/DSCC2008-2185.
4. Hannaford B., *Stability and performance tradeoffs in bi-lateral telemanipulation*, [in:] Proceedings of 1989 IEEE International Conference on Robotics and Automation, Vol. 1763, 1764–1767,
DOI: 10.1109/ROBOT.1989.100230.
5. Hastrudi-Zaad K., Salcudean S.E., *On the use of local force feedback for transparent teleoperation*, [in:] Proceedings of 1999 IEEE International Conference on Robotics and Automation, Vol. 1863, 1863–1869,
DOI: 10.1109/ROBOT.1999.770380.
6. Hogan N., *Impedance Control: An Approach to Manipulation: Part II – Implementation*, “Journal of Dynamic Systems, Measurement, and Control”, Vol. 107, No. 1, 1985, 8–16,
DOI: 10.1115/1.3140713.
7. Ishikiriyama Y., 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, 2010, 143–149,
DOI: 10.1299/jamdsm.4.143.
8. Khadraoui S., Rakotondrabe M., Lutz P., *Interval Modeling and Robust Control of Piezoelectric Microactuators*, “IEEE Transactions on Control Systems Technology”, Vol. 20, No. 2, 2012, 486–494,
DOI: 10.1109/TCST.2011.2116789.
9. Kim W.S., *Developments of new force reflecting control schemes and an application to a teleoperation training simulator*, [in:] Proceedings of 1992 IEEE International Conference on Robotics and Automation, Vol. 1412, 1992, 1412–1419
DOI: 10.1109/ROBOT.1992.220152.
10. Kim W.S., Hannaford B., Fejczy A.K., *Force-reflection and shared compliant control in operating telemanipulators with time delay*, “IEEE Transactions on Robotics and Automation”, Vol. 8, No. 2, 1992, 176–185,
DOI: 10.1109/70.134272.
11. Miądlicki K., Pajor M., *Overview of user interfaces used in load lifting devices*, “International Journal of Scientific & Engineering Research”, Vol. 6, No. 9, 2015, 1215–1220.
12. Miądlicki K., Pajor M., *Real-time gesture control of a CNC machine tool with the use Microsoft Kinect sensor*, “International Journal of Scientific & Engineering Research”, Vol. 6, No. 9, 2015, 538–543.
13. Miadlicki K., Pajor M., Sakow M., *Loader Crane Working Area Monitoring System Based on LIDAR Scanner*, “Advances in Manufacturing”, Springer, 2018, 465–474,
DOI: 10.1007/978-3-319-68619-6_45.
14. Miądlicki K., Pajor M., Saków M., *Ground plane estimation from sparse LIDAR data for loader crane sensor fusion system*, 22nd International Conference on Methods and Models in Automation and Robotics (MMAR), IEEE, Międzyzdroje, Poland, 2017, 717–722,
DOI: 10.1109/MMAR.2017.8046916.
15. Miądlicki K., Pajor M., Saków M., *Real-time ground filtration method for a loader crane environment monitoring system using sparse LIDAR data*, 2017 IEEE International Conference on INnovations in Intelligent SysTems and Applications (INISTA), IEEE, 2017, 207–212, 10.1109/INISTA.2017.8001158.
16. Miądlicki K., Saków M., *The use of machine vision to control the basic functions of a CNC machine tool using gestures*, Czasopismo Techniczne, Vol. 12, 2017, 213–229,
DOI: 10.4467/2353737XCT.17.221.7764.
17. Najdovski Z., Nahavandi S., Fukuda T., *Design, Development, and Evaluation of a Pinch–Grasp Haptic Interface*,

IEEE/ASME Transactions on Mechatronics, Vol. 19, No. 1, 2014, 45–54,
DOI: 10.1109/TMECH.2012.2218662.

18. Nguyen T., Leavitt J., Jabbari F., Bobrow J.E., *Accurate Sliding-Mode Control of Pneumatic Systems Using Low-Cost Solenoid Valves*, IEEE/ASME Transactions on Mechatronics, Vol. 12, No. 2, 2007, 216–219,
DOI: 10.1109/TMECH.2007.892821.
19. Ningbo Y., Hollnagel C., Blickenstorfer A., Kollias S.S., Riener R., *Comparison of MRI-Compatible Mechatronic Systems With Hydrodynamic and Pneumatic Actuation*, IEEE/ASME Transactions on Mechatronics, Vol. 13, No. 3, 2008, 268–277,
DOI: 10.1109/TMECH.2008.924041.
20. Noritsugu T., *Pulse-width modulated feedback force control of a pneumatically powered robot hand*, International Symposium of Fluid Control and Measurement, Tokyo, 1985, 47–52.
21. Pajor M., Miądlicki K., Saków M., *Kinect Sensor Implementation in Fanuc Robot Manipulation*, "Archives of Mechanical Technology and Automation", Vol. 34, No. 3, 2014, 35–44.
22. Polushin I.G., Takhmar A., Patel R.V., *Projection-Based Force-Reflection Algorithms With Frequency Separation for Bilateral Teleoperation*, IEEE/ASME Transactions on Mechatronics, Vol. 20, No. 1, 2015, 143–154,
DOI: 10.1109/TMECH.2014.2307334.
23. Rakotondrabe M., Ivan I.A., *Development and Force/Position Control of a New Hybrid Thermo-Piezoelectric MicroGripper Dedicated to Micromanipulation Tasks*, IEEE Transactions on Automation Science and Engineering, Vol. 8, No. 4, 2011, 824–834,
DOI: 10.1109/TASE.2011.2157683.
24. Rakotondrabe M., Ivan I.A., Khadraoui S., Clevy C., Lutz P., Chaillet N., *Dynamic displacement self-sensing and robust control of cantilever piezoelectric actuators dedicated for microassembly*, 2010 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), 557–562,
DOI: 10.1109/AIM.2010.5695741.
25. Rakotondrabe M., Ivan I.A., Khadraoui S., Lutz P., Chaillet N., *Simultaneous Displacement/Force Self-Sensing in Piezoelectric Actuators and Applications to Robust Control*, IEEE/ASME Transactions on Mechatronics, Vol. 20, No. 2, 2015, 519–531,
DOI: 10.1109/TMECH.2014.2300333.
26. Saków M., Marchelek K., Parus A., Miądlicki K., *Control scheme without force sensors for load sensing in telemanipulation systems with force-feedback*, "Journal of Machine Construction and Maintenance. Problemy Eksploatacji", No. 3, 2017, 21–30.
27. Saków M., Miądlicki K., Parus A., *Self-sensing teleoperation system based on 1-dof pneumatic manipulator*, "Journal of Automation, Mobile Robotics and Intelligent Systems", Vol. 11, No. 1, 2017, 64–76.
28. Saków M., Pajor M., Parus A., *Estimation of environmental forces impact on remote control system with force-feedback and upper limb kinematics* (in Polish), "Modelowanie Inżynierskie", Vol. 27, No. 58, 2016, 113–122.
29. Saków M., Pajor M., Parus A., *Self-sensing control system determining the environmental force influence on the manipulator during the operation of the telemanipulation system* (in Polish), "Projektowanie Mechatroniczne – Zagadnienia Wybrane", Katedra Robotyki i Mechatroniki, Akademia Górniczo-Hutnicza w Krakowie, 2016, 139–150.
30. Saków M., Parus A., *Sensorless control scheme for teleoperation with force-feedback, based on a hydraulic servo-mechanism, theory and experiment*, "Measurement Automation Monitoring", Vol. 62, No. 12, 2016, 417–425.
31. Saków M., Parus A., Miądlicki K., *Predictive method of force determination in the force-feedback communication channel of remotely controlled system* (in Polish), "Modelowanie inżynierskie", Vol. 31, No. 62, 2017, 88–97.
32. Sakow M., Parus A., Pajor M., Miadlicki K., *Unilateral Hydraulic Telemanipulation System for Operation in Machining Work Area,* Advances in Manufacturing, Springer, 2018, 415–425,
DOI: 10.1007/978-3-319-68619-6_40.
33. Saków M., Parus A., Pajor M., Miądlicki K., *Nonlinear inverse modeling with signal prediction in bilateral teleoperation with force-feedback*, 2017 22nd International Conference on Methods and Models in Automation and Robotics (MMAR), IEEE, Międzyzdroje, Poland, 2017, 141–146, 10.1109/MMAR.2017.8046813.
34. Seraji H., Colbaugh R., *Adaptive force-based impedance control*, IROS '93. Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1993, Vol. 1533, 1537–1544,
DOI: 10.1109/IROS.1993.583844.
35. Seul J., Hsia T.C., Bonitz R.G., *Force tracking impedance control of robot manipulators under unknown environment*, "IEEE Transactions on Control Systems Technology", Vol. 12, No. 3, 2004, 474–483, DOI: 10.1109/TCST.2004.824320.
36. Stateczny K., Pajor M., Miadlicki K., Sakow M., *MEMS based system for controlling and programing industrial manipulator Fanuc s-420F using gestures*, "Problemy Eksploatacji", 4/2017, 107, 81–89.
37. Stuart K.D., Majewski M., *Intelligent Opinion Mining and Sentiment Analysis Using Artificial Neural Networks*, International Conference on Neural Information Processing, Springer, Istanbul, Turkey, 2015, 103–110,
DOI: 10.1007/978-3-319-26561-2_13.
38. Stuart K.D., Majewski M., Trelis A.B., *Intelligent semantic-based system for corpus analysis through hybrid probabilistic neural networks*, International Symposium on Neural Networks, Springer, 2011, 83–92,
DOI: 10.1007/978-3-642-21105-8_11.
39. Taghizadeh M., Ghaffari A., Najafi F., *Improving dynamic performances of PWM-driven servo-pneumatic systems via a novel pneumatic circuit*, "ISA Transactions", Vol. 48, No. 4, 2009, 512–518,
DOI: 10.1016/j.isatra.2009.05.001.
40. Takigami T., Oshima K., Hayakawa Y., Ito M., *Application of self-sensing actuator to control of a soft-handling gripper*, Proceedings of the 1998 IEEE International Conference on Control Applications, Vol. 902, 902–906,
DOI: 10.1109/CCA.1998.721589.
41. Wei Tech A., Khosla P.K., Riviere C.N., *Feedforward Controller With Inverse Rate-Dependent Model for Piezoelectric Actuators in Trajectory-Tracking Applications*, "IEEE/ASME Transactions on Mechatronics", Vol. 12, No. 2, 2007, 134–142,
DOI: 10.1109/TMECH.2007.892824.
42. Yokokohji Y., Yoshikawa T., *Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment*, IEEE Transactions on Robotics and Automation, Vol. 10, No. 5, 1994, 605–620,
DOI: 10.1109/70.326566.
43. Yong Z., Barth E.J., *Impedance Control of a Pneumatic Actuator for Contact Tasks*, Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005, 987–992, 10.1109/ROBOT.2005.1570245.
44. Yuguo C., *Self-Sensing Compounding Control of Piezoceramic Micro-Motion Worktable Based on Integrator*, WCICA

2006. The Sixth World Congress on Intelligent Control and Automation, 2006, 5209–5213, DOI: 10.1109/WCICA.2006.1713385.

45. Zhang T., Jiang L., Wu X., Feng W., Zhou D., Liu H., *Fingertip Three-Axis Tactile Sensor for Multifingered Grasping*, "IEEE/ASME Transactions on Mechatronics", Vol. 20, No. 4, 2014, 1875–1885, DOI: 10.1109/TMECH.2014.2357793.

46. Zhou M., Ben-Tzvi P., *RML Glove – An Exoskeleton Glove Mechanism With Haptics Feedback*, IEEE/ASME Transactions on Mechatronics, Vol. 20, No. 2, 2015, 641–652, DOI: 10.1109/TMECH.2014.2305842.

Układ sterowania samowyznaczający obciążenie dedykowany dla zdalnej manipulacji – część 1: teoria

Streszczenie: W artykule przedstawiono nowe podejście do projektowania sterowania dwustronnych systemów teleoperacji z siłowym sprzężeniem zwrotnym, dedykowanym tylko do wykrywania obciążenia w postaci ładunku. Opis problemu, analiza dotychczasowych osiągnięć badawczych oraz zakres badania został zaprezentowany w pracy. Nowy projekt jednostki sterującej dla systemu Master-Slave z siłowym sprzężeniem zwrotnym oparty został na dynamicznym modelu odwrotnym. Model został użyty do odejmowania wartości siły w kanale komunikacyjnym sprzężenia zwrotnego, który może generować system podczas ruchu swobodnego. Ważna część pracy została poświęcona analizie matematycznej obejmującego zjawiska zachodzące w badanym schemacie kontroli.

Słowa kluczowe: zdalna manipulacja, siłowe sprzężenie zwrotne, odwrotne modelowanie, telerobotyka, zdalne sterowanie

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