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Bilateral teleoperation system for a mini crane

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Abstract

In this paper, two automatic mini-crane control systems have been compared; utilizing feedback as well as both feedback and feedforward structures. The proposed control systems were implemented in a Master-Slave system to provide intuitive control for a mini-crane by human muscles. The control systems that have been designed were tested on constructions with similar structures i.e. an upper limb exoskeleton and a mini-crane with two joints, but using different actuation systems. The mini-crane had hydraulic actuators, whereas the exoskeleton was equipped with electrical actuators.

Introduction

If an operator is able to control the overall system in an intuitive way this will increase the safety, accuracy and speed of their tasks. The challenge of this type of control is in designing a system that will not produce undesirable movements. In dangerous situations, the operator's task is to intuitively eliminate the unstable movements of the machine. This problem has been solved in several ways by analyzing the technical solutions, such as:

- the traditional way in the form of operator grips, joysticks, or operator panels (Miądlicki & Pajor, 2015). The need to train the operator in how the system works and also that the operator has to remember the sequence of the program steps are the main disadvantages of this solution. From a practical point of view, only the designer is able to say that the designed control is "normal" for them, which amounts to a subjective evaluation of the control. From a safety point of view, for an inexperienced machine operator in a dangerous situation, the operator could use intuition in a way which will lead him to incorrectly make a move when trying to stabilize the machine. However, despite these disadvantages, solving the problem in this way of human-machine control is quite common and cheap. Designing the control system in this way is not complicated compared to other types of solutions. i.e. the system is not affected by disturbances such as environmental conditions, e.g. weather or environmental vibrations in the form of mechanical or acoustic disturbances;
- voice control (Majewski & Kacalak, 2016) serves to generate commands to the machine using human speech. The control is in one direction and the feedback is shown in the form of a specific task performed by the machine. Additional movements of the operator's body are not needed, which leads to an increase in the operator's working time. The disadvantage of this type of solution is the significantly greater complication of the speech processing itself, which results in an increase of the project's cost. Developing commands and teaching the operator how to control the system is also time-consuming;
- gesture control. The operator performs specific gestures to issue commands to control the crane. For example, by pointing their hand up, to the left

or to the right, the crane will move the working tip in the given direction (Miądlicki & Pajor, 2015; Miadlicki, Pajor & Saków, 2017);
- force feedback control is based on controlling the slave system using the force generated by the operator's muscles. The next step is that the master system senses the dynamics of the slave system (Saków & Parus, 2016). The advantage of this solution is the ability to maneuver the machine in a "narrow environment", for example in a forest, the operator controlling this type of machine has the ability to feel the impact with a tree, and then the operator can quickly respond to any interference. In the field of machines, an interesting example is the positioning of the body units of a CNC machine tool (Herbin, Pajor & Stateczny, 2016), where by using a joystick equipped with force sensors, the operator is able to directly feel the forces acting on the system.
- haptic control is a machine communication technology that communicates through the sense of touch. The operator is able to sense an obstacle from the outside environment. A popular robot that uses this type of control is the da Vinci robot (Hakenberg, 2018), where it is used to carry out complicated operations and the effector's movement is free from vibration, in addition the physician operating the machine is able to sense the patient's skin.

It should be emphasized that the use of any human machine interface makes it possible to control the system from a distance, which increases the safety of the system's operator. The basis of the control system that has been proposed in this article is a control system equipped with force feedback. The purpose of the control system is to enable a sense of the dynamics of the Slave system in the Master system.

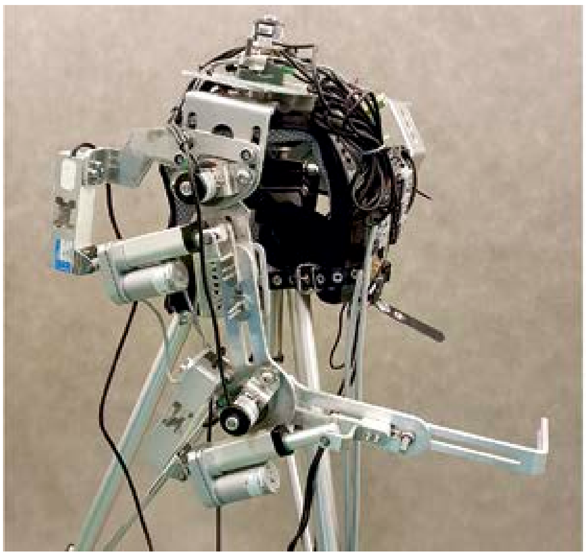
The proposed Master-Slave control system

The mechatronic system that has been presented in this article combines areas such as: hydraulics and electrics (actuator system), mechanics (dynamic system – exoskeleton and mini-crane), electronics (measurement of physical quantities and control signals) and automation (the right to control as well as digital signal processing).

Experimental stand

The system can be described as a Master-Slave system. The Master system is in the form of an exoskeleton, it works with an operator and includes the exoskeleton's executive subsystem in the form of electric actuators, a control system and measured signals i.e. the angular position of the exoskeleton's joints and the force acting on the strain gauge beams. The Slave system is a hydraulically controlled mini crane whose actuators were in the form of cylinders which were controlled by proportional valves. The measurement system of the Slave system included such signals as: the position of the valve spool, the coil current, the angular position of the mini crane's joints and the environmental forces. The above-mentioned signals were included in the control system. The master and slave devices have been presented in Figure 1.

a)



b)

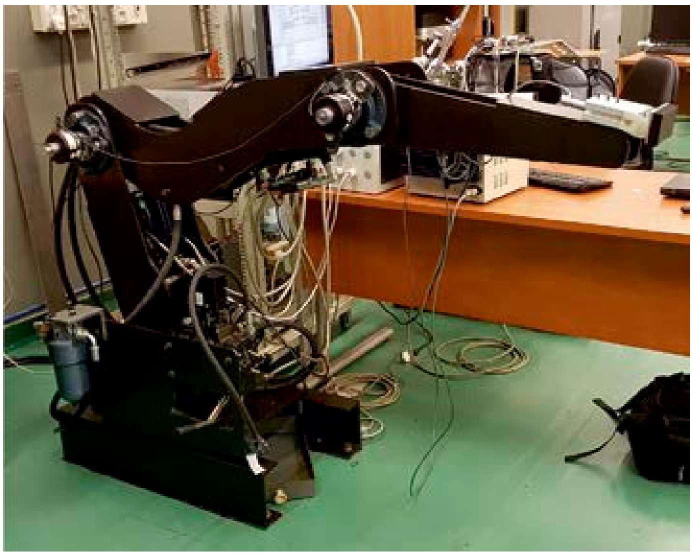


Figure 1. The experimental stand, a) Master system b) Slave system

Challenges of the Master-Slave control system

In this type of system, several problems can be observed from the design level of the control system, which are divided into the different parts of the Master and Slave sub-systems. A diagram of the kinematic structure has been presented in Figure 2.

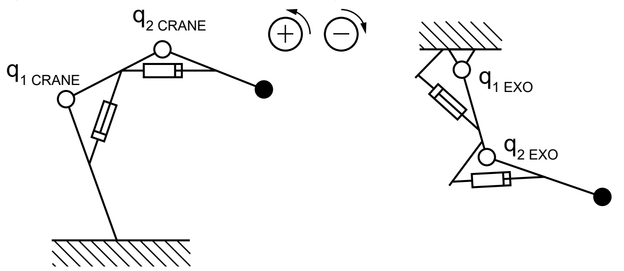


Figure 2. Diagram of the kinematic structure of a) the Slave system and b) the Master system

Challenges of the Master system:

- friction and assembly clearance cause non-continuous movement of the exoskeleton's joints;
- the asymmetrical weight distribution of the exoskeleton, which results in the reduced comfort of the control system;
- the system is non-stationary when operational (Pajor, Marchelek & Powalka, 1999).

Challenges of the Slave system:

- the dynamic non-linearity of the executive system resulting from the different cross-sections of the hydraulic actuator chambers (Morales & Hera, 2012);
- spooler friction in the proportional valve, which controls the flow of fluid in the hydraulic crane system. A common solution to this is the implementation of dither (Amirante, Innone & Catalano, 2008). The application of micro vibrations in the system reduces the coefficient of friction. Dither parameters, i.e. frequency and amplitude, can be adjusted to simultaneously obtain a satisfactory reduction in the friction coefficient along with the absence of any observable vibration in the actuator (Gutowski & Leus, 2012);
- current hysteresis in the hydraulic valve coils – the implementation of the identified static hysteresis loop supports the current regulation.

The structure of the intuitive control systems

The entire system was built from three subsystems, which have been shown graphically in Figure 3, they consisted of:

- a crane – the working system, whose task is to transfer the load from point A to B. The trajectory of its motion is based on the strength of human muscles, which is read by the exoskeleton. In addition, the working system sends feedback to the operator, informing them about any environmental obstacles.
- an exoskeleton (operator) – a mini-crane control system which uses an automatic adjustment system to inform the operator about the position of the crane and any environmental impact.
- Matlab/Simulink + dSPace – a regulator that calculates the appropriate value, controlling the exoskeleton and mini crane, based on the measurement of the state variables.

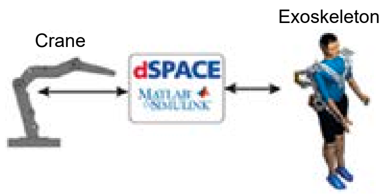


Figure 3. Diagram of the intuitive mini crane control system

The idea of the control system has been presented in Figure 4. The task of the exoskeleton is to follow the angular position of the mini-crane. The movement of the mini-crane depends on the forces from the exoskeleton F_{EXO} and the environmental forces F_{CRANE}. The presented system consisted of two control systems:

- the crane control system – which calculates the control signal u_{CRANE} in order to perform the movement of the mini-crane and the control signal of exoskeleton's movement $u_{\mathrm{exo\ feedforward}}$ according to the forces F_{EXO} and F_{CRANE};
- the exoskeleton control system – which calculates the control value necessary to follow the mini crane's angular position. The error is described as the difference between the individual rotational position of the mini crane and the rotational position of the exoskeleton – as described in Equation (1):

$$\lim_{t\to\infty} e_q(t) = q_{\mathrm{CRANE}}(t) - q_{\mathrm{EXO}}(t) = 0 \qquad (1)$$

The outline of the system's operation that has been presented above is a simplified description of the intuitive mini-crane control from the level of the exoskeleton. At its basis is an extended version of the control system description which was implemented in order to carry out the experiment. A graphical presentation of the physical signal flow throughout the system has been shown in Figure 5.

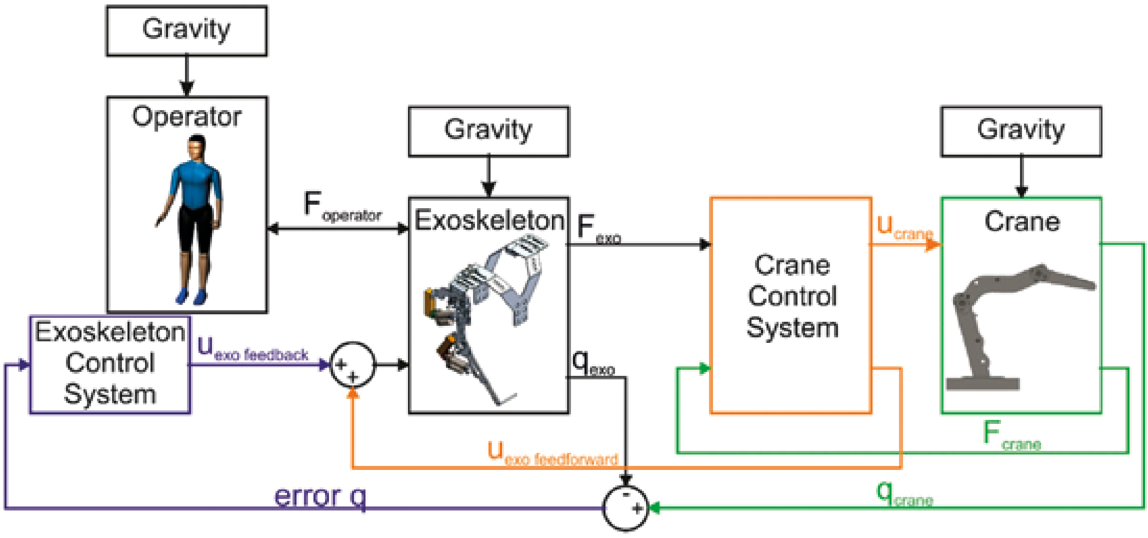


Figure 4. The outline of the mini crane control system

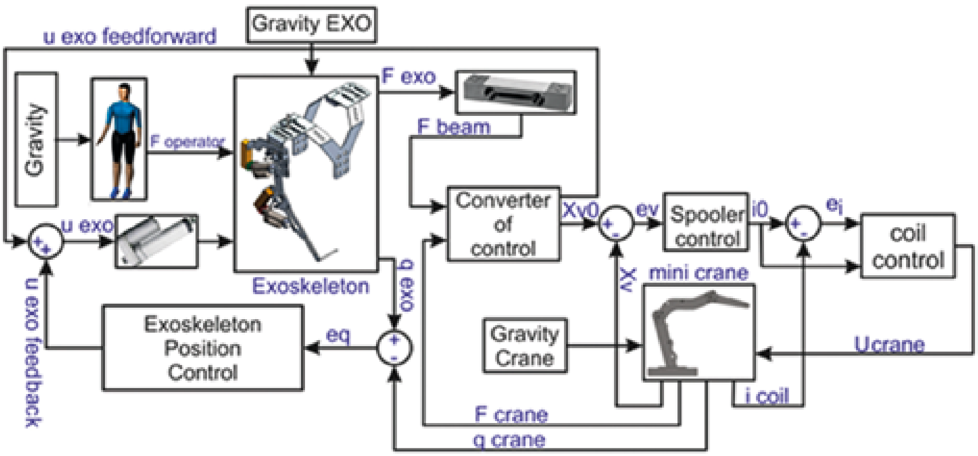


Figure 5. Diagram of the extended intuitive control system of a mini-crane

The input signal to the control system consisted of the forces: F_{CRANE}, which originates from the environmental sensor; F_{BEAM} – the exoskeleton force measured by the strain gauge beams and extracted from the interaction force between the exoskeleton and the operator F_{EXO}.

The value of the force F_{EXO} is a combination of three forces:

1) the force due to gravity – the load torque from the force due to gravity depends on the configuration angle of the system (Wittbrodt, Adamiec-Wójcik & Wojciech, 2007);
2) the forces of the exoskeleton actuator $F_{\text{electric actuator}}$ – the movement of the exoskeleton joints depends on the force generated by the electric actuator, whose aim is to compensate for the angular position error between the exoskeleton and the crane;
3) the operator force F_{operator} – generated by the strength of human muscles, this is generated by the operator in order to make the mini-crane move.

The mini-crane control system generates an electromagnetic force in the hydraulic coil causing the movement of the valve spooler x_v. The result of the movement of the spooler is the flow of liquid into the proportional valve, generating a force that acts on the individual mini-crane's joints. In the mini-crane control system, a cascade regulator structure that consisted of three elements was proposed:

- a control converter – this controls the safe operation of the crane (operation in the working area) and generates two control signals for the crane x_{v0} and the exoskeleton $u_{\text{exo feedforward}}$;
- a valve spooler regulator – which calculates the signal i_0 in order to compensate for the error between the set initial position of the spooler valve x_{v0} and the actual spooler position x_v. The controller PI, along with resetting the integrator

at the error transition through zero, has been used in order to achieve a soft start onto the next move of the spooler;

- a current regulator for the hydraulic coils – the electromagnetic force generated in the coil, proportional to the current i, causes the movement of the spooler x_v. The controller calculates the signal u_{CRANE} in order to compensate for the error between the current i and the actual set point i_0. The structure of the current regulator was designed in the form of two couplings:
  1) Feedforward control – the task is to increase the dynamics of the coil current. The inverse model of the coil is based on the identified static characteristics;
  2) Feedback control – compensation for the disturbances and possible imperfections of the identified coil model – PI controller.

For control of the exoskeleton system, forward and reverse control was implemented. The feedforward regulator could be used, because the velocity of the exoskeleton electrical actuators was faster than the velocity of the hydraulic actuators. If only the feedback regulator was used, the system would lose its stability i.e. oscillations of the mini-crane and the exoskeleton's angular position would be observed. In the feedback structure, a proportional controller has been implemented, whose control signal $u_{EXO\ FEEDBACK}$ is proportional to the error between the position of the crane's joints q_{CRANE} and the position of the exoskeleton's joints q_{EXO}. In the feedforward structure, the control signal $u_{EXO\ FEEDBACK}$ is added to the signal $u_{EXO\ FEEDFORWARD}$, according to Equation (2):

$$u_{EXO} = u_{EXO\ FEEDFORWARD} + u_{EXO\ FEEDBACK} = \\ = u_{EXO\ FEEDFORWARD} + P \cdot (q_{CRANE} - q_{EXO}) \quad (2)$$

The P type regulator was used because it is not characterized by a phase shift. The P value has been adjusted in order to avoid large oscillations of the exoskeleton worn by the operator.

The disadvantage of the extended intuitive control system of a mini-crane is the lack of compensation for gravity acting on the strain gauge beams which causes a static error of two degrees between the angular position of the corresponding components of the mini-crane and the exoskeleton. However, this value is low enough to not be felt during the operation of the mini-crane. In order to minimize this error, compensation for the force due to gravity was applied by introducing the exoskeleton's dynamics model into the control system.

Experimental methodology and results

Two Master-Slave control systems were tested; the first case considered a mini-crane control system with a feedback structure, the second case also included a feedforward structure.

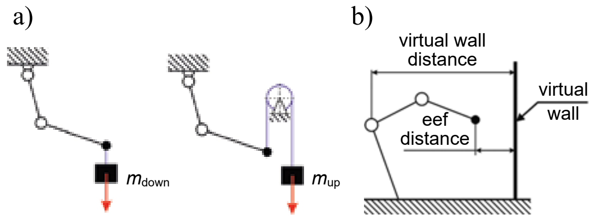


Figure 6. Diagram of the experimental stand configuration a) the first scenario of the experiment, b) the second scenario of the experiment

Two scenarios for the experiment of the control systems were carried out. The first test consisted of loading particular exoskeleton joints with a constant force in the direction of gravity (the red arrow in figure 6a is gravity's force vector). The arm of the exoskeleton was picked up and dropped in accordance with the diagram shown in Figure 6a. The aim of this test was to perform joint movements in their full range to check the stability of the proposed mini-crane control systems.

The position of the exoskeleton's joint (q1 EXO) followed the mini-crane's joint position (q1 CRANE) during the 1^{st} scenario of the experiment using the mini-crane control system with force feedback structure (see Figure 6a). However, it was observed that the positioning of the arm was jerky. This was caused by the too low elasticity of the exoskeleton's actuator system, and also the greater dynamics of the Master system's actuators with respect to the Slave system's actuators.

The force measured by the strain gauge beam on the exoskeleton *joint q1* oscillated during the movement of the exoskeleton arm, as shown in Figure 7b. In order to ensure the safety of the system during the tests, the results of which have been shown in Figure 7, the angular range was limited to 32 degrees. These system instabilities resulted from the excessive speed of the exoskeleton actuators relative to the crane actuators. As can be observed in Figure 8, jerking of the position of the joints, as well as oscillations in the force were significantly reduced by using the mini-crane control system with force feedback and feedforward structures. Utilizing this control system, it was possible through programming to obtain a reduction in the stiffness of the exoskeleton's actuation system

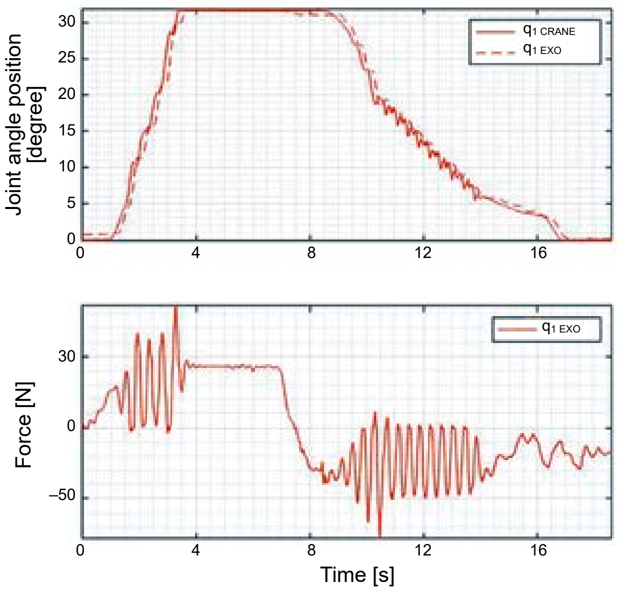


Figure 7. a) Exoskeleton joint and mini-crane joint position and b) the force measured by the strain gauge beam during the 1st scenario of the experiment using the mini-crane control system with force feedback structure

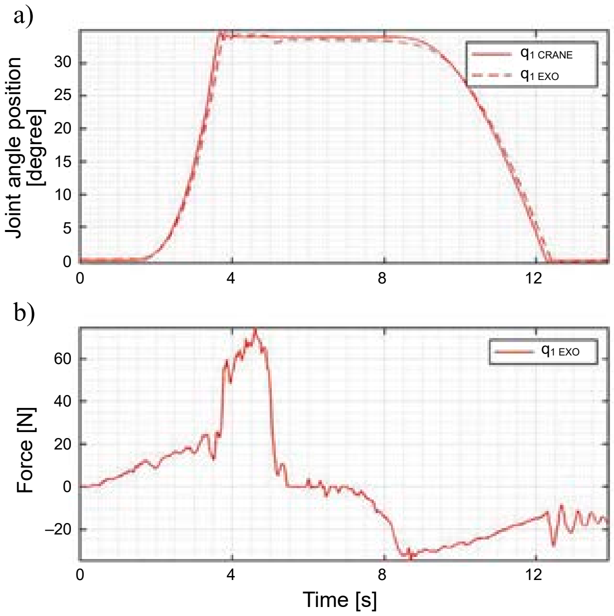


Figure 8. a) Exoskeleton joint and mini-crane joint position and b) the force measured by the strain gauge beam during the 1st scenario of the experiment using the mini-crane control system with force feedback and feedforward structures

The second scenario of the study took into account the contact of the crane with the virtual environment i.e. an obstacle in the form of a virtual wall was simulated. The Virtual Wall distance was the distance between the first joint and the end effector of the robot. The experiment consisted of hitting the virtual wall and then investigating how deeply the effector was pushed into the virtual wall. How the environment of the Slave system was felt in the Master system, i.e. by the operator, was also tested. A diagram of the experimental stand has been presented in Figure 6b.

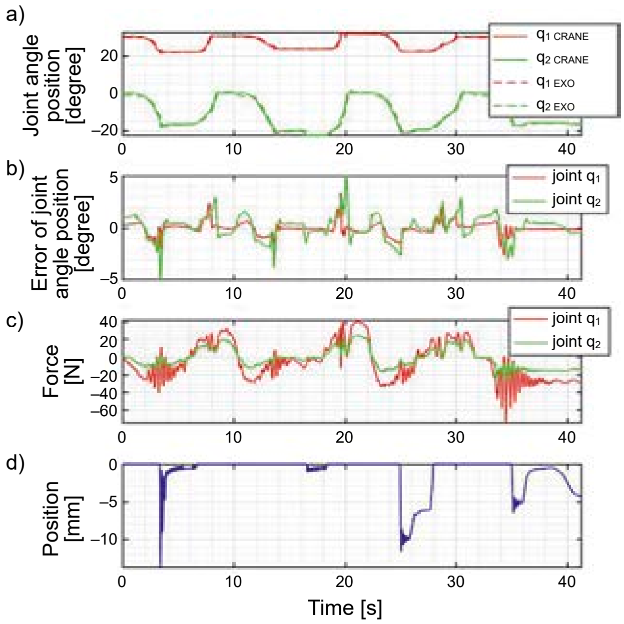


Figure 9. a) Position of the exoskeleton and the mini-crane joints *q1* and *q2* b) position error c) force measured by the strain gauge beams located on joints *q1* and *q2* d) depth of penetration into the obstacle by the end tip of the mini-crane during the 2st scenario of the experiment using the mini-crane control system with force feedback structure

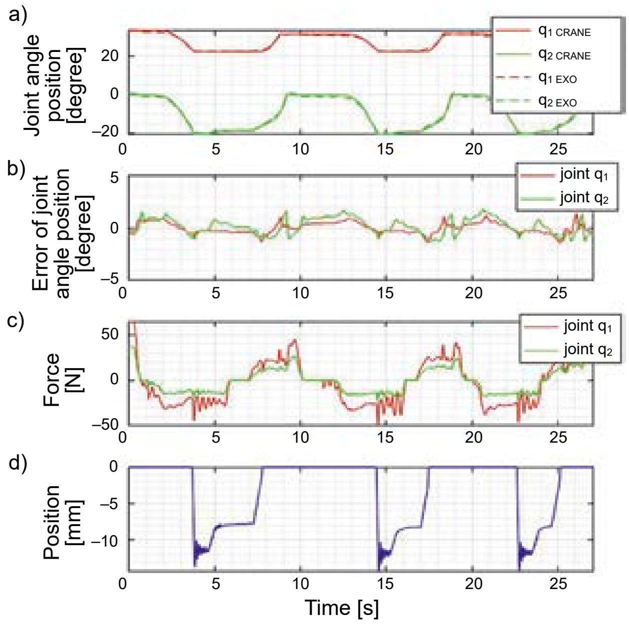


Figure 10. a) Position of the exoskeleton and mini-crane joints *q1* and *q2* b) position error c) force measured by the strain gauge beams located on joints *q1* and *q2* d) depth of penetration into the obstacle by the end tip of the mini-crane during the 2st scenario of the experiment using the mini-crane control system with force feedback and feedforward structure

Comparing the results that have been presented in Figures 9 and 10, a significant reduction in the position error can be seen after the addition of the feedforward structure to the mini-crane control system. The maximum position error observed during this part of experiment decreased from over 5° to 1.5°. Both the amplitude and the amount of oscillation of the forces, measured by the strain gauge beams on the exoskeleton's *joint q1* and *joint q2*, also decreased. The stability that was obtained by the Master-Slave control system with feedforward structure allowed for repetitive contact with the virtual wall to be performed. Feeling the impact of the virtual wall, using only the feedback regulator, does not reflect reality, while the impact of the obstacle was felt by the operator during the experiment with the feedback and feedforward regulator.

Conclusions

In the analysis of the two control systems of the mini-crane that have been presented, the addition of the feedforward structure caused an increase in the damping coefficient, that resulted in a reduction of the oscillation of the forces. There was a reduction in both their amplitude and amount. As the result the person operating the system was able to feel the mini-crane's environment through the upper limb exoskeleton. Operation using both the feedforward and feedback control system was characterized by the repeatability of the mini-crane's movement. The designed control system has accomplished the main goal of the research work, which was the stable and effective control of a mini crane by the exoskeleton using force feedback. The drawback of the mini-crane hydraulic system is that it has large inertia with respect to the exoskeleton's actuation systems. The solution to this problem may be the implementation of servo valves, which will increase the dynamics of the hydraulic system. The plan for future research is to reduce the weight of the exoskeleton and replace the proportional hydraulic valves in the mini crane control system (slave system) with servo valves.

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References

1. Amirante, R., Innone, A. & Catalano, L.A. (2008) Boosted PWM open loop control of hydraulic proportional valves. *Energy Conversion and Management* 49, 8, pp. 2225–2236.
2. Gutowski, P. & Leus, M. (2012) The effect of longitudinal tangential vibrations on friction and driving forces in sliding motion. *Tribology International* 55, pp. 108–118.
3. Hakenberg, O.W. (2018) A brief overview of the development of robot-assisted radical prostatectomy. *Arab journal of urology* 16, 3, pp. 293–296.
4. Herbin, P., Pajor, M. & Stateczny, K. (2016) Six-axis control joystick based on tensometric beam. *Advances in Manufacturing Science and Technology* 40, 4, pp. 33–41.
5. Majewski, M. & Kacalak, W. (2016) *Human-machine speech-based interfaces with augmented reality and interactive systems for controlling mobile cranes*. In: International Conference on Interactive Collaborative Robotics, Springer, Cham, p. 89–98.
6. Miądlicki, K. & Pajor, M. (2015) Overview of user interfaces used in load lifting devices. *International Journal of Scientific & Engineering Research* 6, 9, pp. 1215–1220.
7. Miądlicki, K. & Pajor, M. (2015) Real-time gesture control of a CNC machine tool with the use Microsoft Kinect sensor. *International Journal of Scientific & Engineering Research* 6, 9, pp. 538–543.
8. Miądlicki, K., Pajor, M. & Saków, M. (2017) Loader Crane Working Area Monitoring System Based on LIDAR Scanner. *Advanced in Manufacturing*, pp. 465–474.
9. Morales, O.D. & Hera, P.M. (2012) *Modeling dynamics of an electro–hydraulic servo actuated manipulator: A case study of a forestry forwarded crane*. IEEE: World Automation Congress.
10. Pajor, M., Marchelek, K. & Powalka, B. (1999) Experimental verification of method of machine tool-cutting process system model reduction in face milling. *WIT Transactions on Modelling and Simulation* 22.
11. Saków, M. & Parus, A. (2016) Sensorless control scheme for teleoperation with force-feedback, based on a hydraulic servo-mechanism, theory and experiment. *Measurement Automation Monitoring* 62.
12. Wittbrodt, E., Adamiec-Wójcik, I. & Wojciech, S. (2007) *Dynamics of flexible multibody systems: rigid finite element method*. Springer Science & Business Media.