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REMOTE CONTROL OF THE MECHATRONIC REDESIGNED SLIDER-CRANK MECHANISM IN SERVICE

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Abstract. *Slider-crank mechanisms are used in many machines where there is a need to transform rotary motion into translation, and vice versa. Implementation of the control into a mechanical assembly of the slider-crank mechanism offers a wide range of applications of such controlled mechanism in mechatronic systems. This paper shows an example of the remote control of the angular velocity of the crank in a mechatronic redesigned slider-crank mechanism in order to achieve the desired motion of the slider. The remote control is achieved over the Internet connection and the appropriate software which is executed in the user's internet browser. The aim of this paper is to present the applied control algorithm as well as to explain advantages of the possibility to remotely run a mechatronic redesigned slider-crank mechanism in service. This is done through an example of using a controlled slider-crank mechanism in a remote laboratory experiment.*

Key Words: *Slider-crank Mechanism, Remote Control, Mechatronic System, PID Controller, NI LabVIEW*

1. INTRODUCTION

The main function of any mechanism is the realization of motion. The most common case is that of converting rotary motion of the crank (motor shaft rotation) into a rotary motion (rocker motion) or translational motion of the output link (the slider of the slider-crank mechanism).

Thanks to the fast development of computers and microprocessors, mechatronics as a discipline which is a synergy of mechanical engineering, electronics, computer science and control, offers great opportunities for the development and improvement of complex technical

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systems [1]. One of the main tasks of mechatronics is to upgrade existing mechanical systems by implementing additional control functions, particularly in precision engineering, in order to make these systems more functional, with better performance, consuming less power, performing safer and so on. Likewise, by implementing the mechatronic approach into the design of mechanisms, it is possible to convert classical mechanical assemblies into mechatronic mechanisms which are more useful and adaptive to different tasks in mechatronic systems. Typical examples of using mechatronic mechanisms are the following [2]:

- use of mechanisms for transforming rotary motion into translation (for example at slider-crank mechanisms) with appropriate controllable actuators, as a simple constructive solution for the generation of a linear translation of the motion patterns that can be controlled,
- using of mechanisms for path generation with the degree of freedom F=1, for the generation of specified path and control of the velocity profile along this path by using appropriate controllable actuator,
- using of mechanisms for the path generation with the degree of freedom F=2, for the generation of the specified path by a main drive at constant velocity and one auxiliary drive with controlled velocity or by two controlled actuators,
- using of appropriate controllable actuators for driving mechanisms with the non-uniform transmission in order to reduce the required driving torque by controlling the drive,
- using of appropriate controllable actuators for driving mechanisms with the non-uniform transmission in order to reduce the non-uniformity of motion by controlling the drive (instead of using the flywheel), and,
- using of appropriate controllable actuators for driving mechanisms with the non-uniform transmission in order to minimize the effects of the shaking forces and shaking torques on the frame by controlling the drive (instead of using the counterweights).

The effectiveness of use of these options requires, already at the planning stage for their application, an integrated observation of the whole system and the kinematics of the mechanism as well as the operating characteristics of the applied actuator, in particular for driving mechanisms with the non-uniform transmission.

In this paper a feasibility study for controlling the motion of a mechatronic redesigned slider-crank mechanism is elaborated. For that case, different approaches can be found in references. By using the particle swarm optimization (PSO) algorithm, a novel design method for the self-tuning PID control in a slider–crank mechanism system is presented in [3]. The paper demonstrates, in detail, how to employ the PSO so as to search efficiently for the optimal PID controller parameters within a mechanism system. In [4] a supervisory fuzzy neural network (FNN) controller is proposed to control a nonlinear slider-crank mechanism where the control system is composed of a permanent magnet (PM) synchronous servo motor drive coupled with a slider-crank mechanism and a supervisory FNN position controller. In [5] "Mechatronic redesign'' of the slider-crank mechanism is carried out in order to perform a variety of motion patterns. A novel design for quick return mechanisms, where the new mechanism is composed by a generalized Oldham coupling and a slider-crank mechanism is proposed in [6]. In [7] the mathematical model of the motor-mechanism coupling system is developed. To formulate the equation of motion, the Hamilton's principle and the Lagrange multiplier method are applied. An adaptive controller for the motor-mechanism coupling system is obtained by using the stability analysis with the inertia-related Lyapunov function. [8] shows a similar approach for the control algorithm. The experiment is carried out in the virtual environment, where SolidWorks CAD design software is used for modeling the mechanism which is then linked to NI LabVIEW graphical programming platform that is used to control the mechanism. In [9] the variable structure control (VSC) and the stabilizer design by using pole placement technique are applied to the tracking control of the flexible slider-crank mechanism under impact. The VSC strategy employed to track the crank angular position and velocity, while the stabilizer design is involved to suppress the flexible vibrations simultaneously. In [10] regulation and vibration control of a flexible slider–crank mechanism is presented. The PDA controller composed of the traditional proportion and derivative controllers with the feedback of acceleration of the crank are derived by using the Lyapunov's direct method. Suppression of the elastodynamic vibrations of a slider-crank mechanism with a very flexible connecting rod is addressed in [11]. A model for the mechanism is derived using Euler-Lagrange equations and the assumed modes method. The control action uses two feedback signals: the crank angle and the connecting rod coupler midpoint deflection. Two control schemes are proposed for the control of the flexible slider-crank mechanism. One scheme is a simple PD control scheme with feedback linearization. The second scheme is based on the μ-synthesis control technique. In [12] a method of solution rectification by means of transmission angle control which can be used to parameterize a problem to prevent the evaluation of invalid linkages is presented. The solution takes into consideration crank driven and slider driven mechanisms as well as a reversible driver mechanism. Dynamic behavior of a slider–crank mechanism associated with a smart flexible connecting rod is investigated in [13]. Two control schemes are proposed; the first is based on feedback linearization approach and the second is based on a sliding mode controller. In [14] an optimization method is proposed to alleviate the undesirable effects of joint clearance in order to optimize the mass distribution of the links of a mechanism to reduce or eliminate the impact forces in the clearance joint. For a slider–crank mechanism with a revolute clearance joint between the slider and the connecting rod, an algorithm based on PSO is used. In [15] a numerically comparative study on dynamic response of a planar slider–crank mechanism with two clearance joints between considering harmonic drive and link flexibility is conducted. The comparative study of optimization design of the rigid and harmonic drive slider–crank mechanism experiencing wear is also presented.

The aim of the research presented in this paper is focused on using the control algorithm for the generation of a linear translation of the motion patterns that can be controlled as well as for explaining the possibility of remote running of the given task. This remote experiment shows an example of the control of the crank angular velocity in a slider-crank mechanism in order to achieve the desired motion pattern of the slider. Slider-crank mechanisms are used in many machines where there is a need to transform rotary motion into translation, and *vice versa*. As with most other mechanisms, for driving slider-crank mechanisms motors with the constant angular velocity are generally used. In that case, the driven motion of a slider-crank mechanism represents the return stroke of the slider for each cycle of rotation of the driving member, which is called a crank. For a centric slider-crank mechanism, the working and the return strokes of the slider have the same duration. If an application requires a mechanism with the slower working stroke (e.g. for the realization of operations of cutting, copying, scanning, deep sheet metal drawing, etc), and at the same time, the rapid return stroke (there are not working operations in the return stroke, it is just necessary to bring back the mechanism to its starting position quickly in order to save the time up to the next working operation), the traditional approach to solving this problem offers a complete redesign of the mechanism structure only.

Such a requirement, however, could be effectively carried out as well by installing appropriate sensors for determining the position of the crank and appropriate controllable actuators that would be able to change the angular velocity of the crank of a slider-crank mechanism. Such a "mechatronic redesign", by using appropriate sensors, control systems and controllable drive actuators, adapts a traditional slider-crank mechanism in order to be able for implementing a variety of different motion-controlled transfer functions without any additional changing of the basic mechanism structure.

2. Components of Mechatronic Redesigned Slider-Crank Mechanism

2.1. Mechanical assembly of mechatronic redesigned slider-crank mechanism

The mechanical assembly of the mechatronic redesigned slider-crank mechanism is shown in Fig. 1. It consists of several parts: crank (1), coupler (2), small wheel (3), guide frame (4), crank carrier (5), pin (6), DC motor with rotary encoder (7) and two plates (8).

The two plates are connected thus representing the frame for the mechanism. The front plate has three slots. The two longer and narrower slots are used for screwing the motor, while the third shorter and wider one is used for the motor shaft. The crank carrier is connected to the motor shaft. The guide frame is placed on the front plate. The small wheel is actually a ball bearing, that acts as the slider and it slides along the guide frame with neglected friction. It is connected to the coupler by the pin. The crank is connected on one side with to the crank carrier and on another to the coupler.

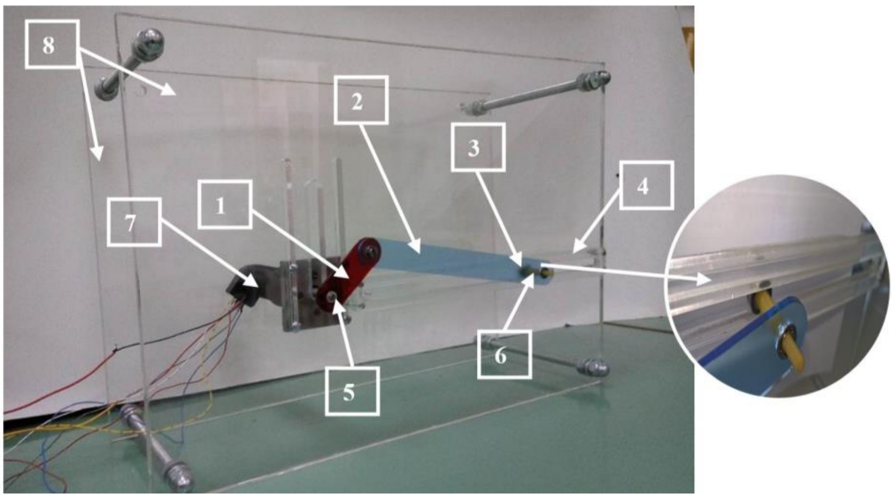

Fig. 1 Mechanical assembly of mechatronic redesigned slider-crank mechanism

2.2. Electronics of mechatronic redesigned slider-crank mechanism

For this experiment the servo DC motor Faulhaber 3272G024CR shown in Fig. 2a is used for driving the mechanism crank. Since this motor is intended to rotate in one direction only, the simple electric driver, whose electric scheme is shown in Fig. 2b, is used to drive the motor. This electric controller consists of one resistor of 3kΩ, one transistor BDX33C, and one diode. The controller is connected to the motor, and to the multifunction I/O device NI USB 6363 whose fast digital output is used to achieve the pulse width modulation (PWM) for controlling the voltage supply for the motor. Fig. 2c shows the NI USB 6363 device. On the back side of the motor shaft, the rotary encoder HEDS 5540 A12 is mounted. Fig. 2d shows the encoder which has 500 pulses per revolution. This encoder is directly connected to the NI USB 6363 device on the corresponding fast digital input ports.

There is also a web camera connected to the computer for video live streaming during the execution of the experiment.

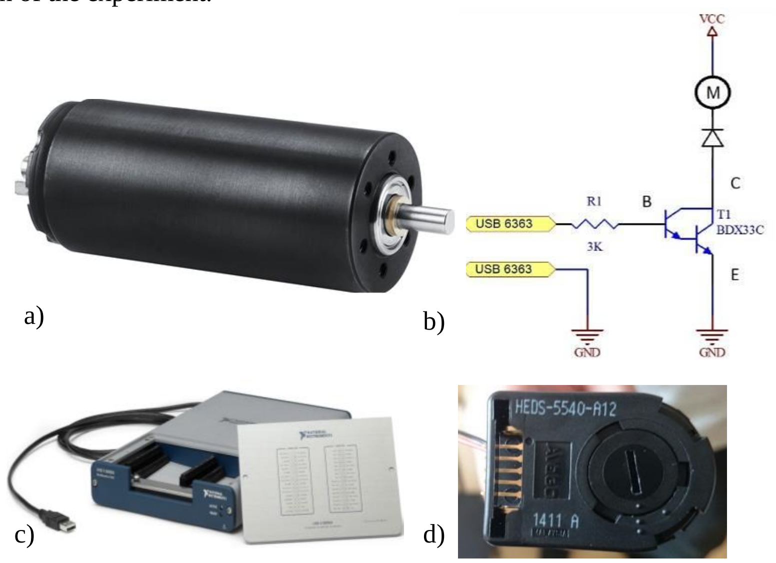

Fig. 2 Electronic components of mechatronic redesigned slider-crank mechanism a) DC motor, b) electric driver, c) NI USB 6363 device, d) encoder

3. Transfer Function of Slider-Crank Mechanism

As already mentioned, the drive for the crank is the servo DC motor with the embedded rotary encoder. Because the control of the motion of the slider is the aim, it is necessary to know current values of the position or the velocity of the slider of the mechatronic redesigned slider-crank mechanism in service. These values are not easy to measure because of complex movable parts; that is why the encoder on the motor shaft that drives the crank is used for that purpose. The encoder measures the angle of the crank position, and by the transfer function of the (centric) slider-crank mechanism (Fig. 3) described by equations below, the position of the slider can be determined:

$$s(\varphi) = a\cos\varphi + c\cos\gamma\ , \tag{1}$$

where s represents the position of the slider, φ represents the angular position of the crank, a represents the crank length, c represents the coupler length. Since angle γ can be calculated by the equation:

$$\gamma = \arcsin \frac{a \sin \varphi}{c}, \tag{2}$$

the complete transfer function of the centric slider-crank mechanism can be represented as:

$$s(\varphi) = a \cos \varphi + c \cos(\arcsin \frac{a \sin \varphi}{c}), \tag{3}$$

which is used for the following procedure of controlling the mechatronic redesigned slider-crank mechanism. The transfer function enables calculating the current position of the slider in dependence on the current angular position of the crank measured by the rotary encoder on the motor shaft. Positions of the slider in two adjacent moments are used for numerical differentiation with respect to time for estimating the current velocity of the slider.

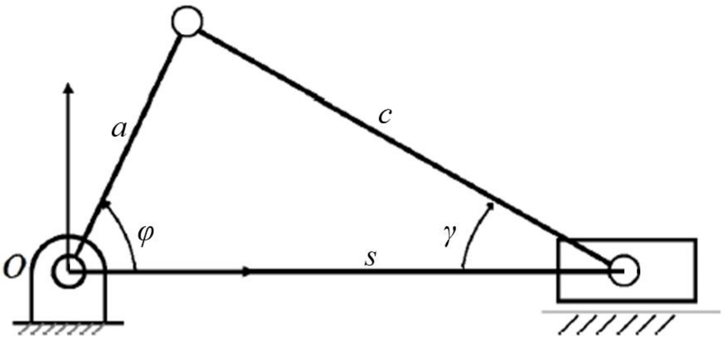

Fig. 3 Kinematic scheme of centric slider-crank mechanism

4. CONTROL CONCEPT OF MECHATRONIC REDESIGNED SLIDER-CRANK MECHANISM

As already explained, the position of the slider of the mechatronic redesigned slider-crank mechanism can be determined by using the angular position of the crank measured with the rotary encoder and the transfer function of the centric slider-crank mechanism (3). Moreover, it is necessary to define the desired velocity profile of the slider. For this example, it is decided to use desired velocity profile $v(t)$ of the slider shown in Fig. 4, because such an example can have the most common use in practice. Time t_1 represents the time that the slider remains in the initial position, t_2 is the time of the slider motion in one direction (the operating motion), time t_3 is the time of the slider rests after the operation motion, t_4 is the time of the slider motion in the other direction (the return motion). Time t_u represents the time of acceleration and deceleration of the slider during the transition from a steady state to a motion state, and *vice versa*, and it depends on the motor power, the mass of the members of the mechanism, friction in joints and the guide frame, etc.

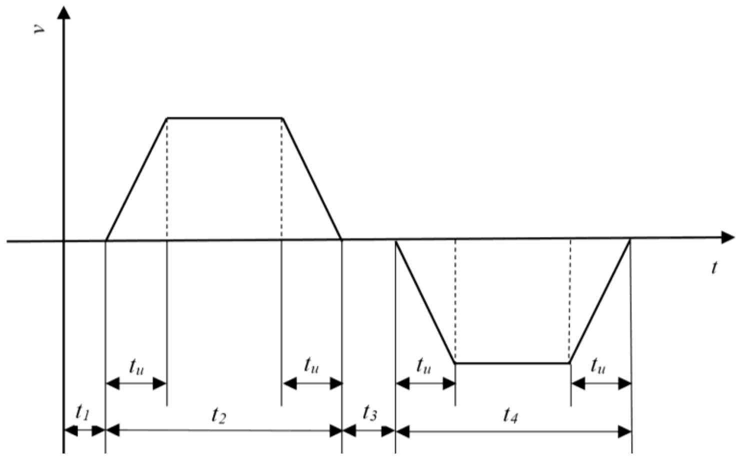

Fig. 4 Desired slider velocity profile

The difference between the desired and the estimated slider velocity, obtained by numerical differentiation with respect to time of the transfer function (3), as explained previously, returns the error in the slider velocity which should be corrected by the PID control. The equation of the PID controller is the following:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt} \tag{4}$$

where K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, *e(t)* is the error and $u(t)$ is the output from the PID controller.

The output from the PID controller is percentage for the width of the PWM signal, i.e. a duty cycle of the PWM signal, and on this way the PID controller adjusts the supplying voltage for the motor. The user can set parameters of the PID controller and exactly on these parameters depends how well the slider will perform the desired motion. Fig. 5 represents the block diagram of the control algorithm.

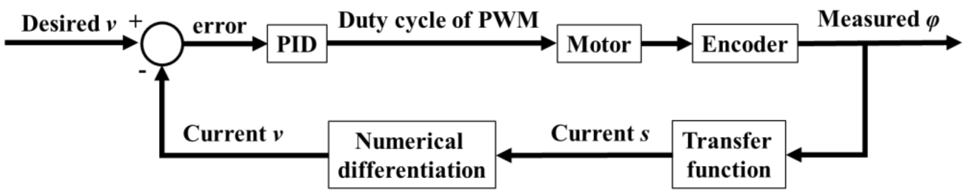

Fig. 5 Block diagram of control algorithm

5. MECHATRONIC REDESIGNED SLIDER-CRANK MECHANISM IN SERVICE AS REMOTE LABORATORY EXPERIMENT

It is not always feasible to set up a classroom experiment because of lack of funds. Nowadays, the Internet opens completely new possibilities by allowing users to perform remote dislocated laboratory experiments in very much the same way, or nearly the same way as operating them on the spot.

In this paper the example of a remote laboratory experiment is shown on the remote control of the previously described mechatronic redesigned slider-crank mechanism stationed at the Mechatronic Laboratory of the Faculty of Mechanical Engineering of University of Niš, Serbia. Fig. 6 shows the starting interface with the Parameters and Control layout where the user can set the parameters of the slider-crank mechanism, the parameters of motion and rest as well as the gains of the PID controller. In this example, the gains of the PID controller are experimentally obtained. On the same interface calculated and measured positions of the slider can be observed.

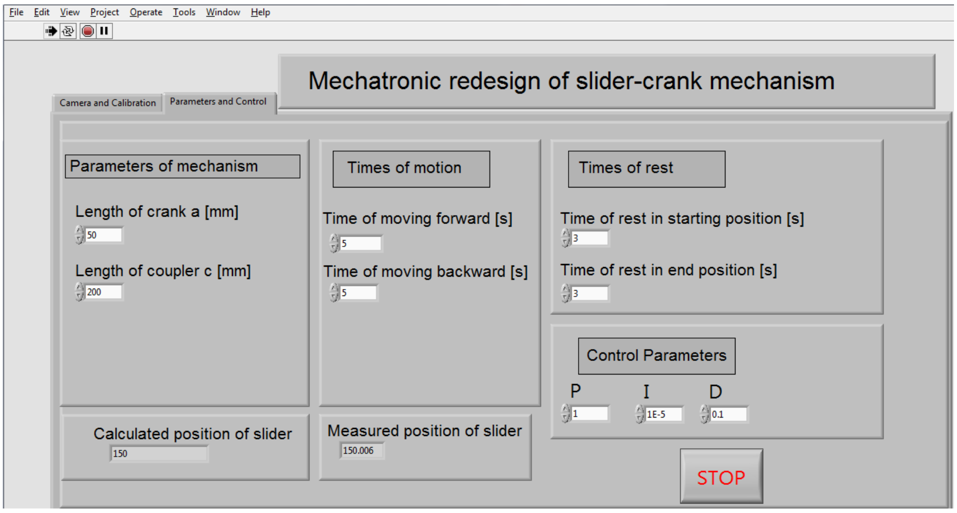

Fig. 6 Starting user interface for setting parameters for remote control of mechatronic redesigned slider-crank mechanism

It should be noted that, due to the use of relative rotary encoder, the considered mechatronic redesigned slider-crank mechanism should be firstly brought into the inner limit position as a starting position (Fig. 7), because the transfer function equations are written as relative to this position, and only then it is possible to start the motion. In the Camera and Calibration layout with the video live streaming there is a possibility of calibration and adjustment of the mentioned mechanism starting position using buttons **Rough** and **Fine**. Pressing and holding of the button **Rough** causes the rotation of the crank into the counterclockwise direction at approximately 60 °/s and pressing and holding of the button **Fine** causes the rotation of the crank into the counterclockwise direction at approximately 1 °/s. With the help of the camera stream it is possible to bring the mechatronic redesigned slider-crank mechanism into the necessary starting position. Pressing the **Done** button will save the starting position.

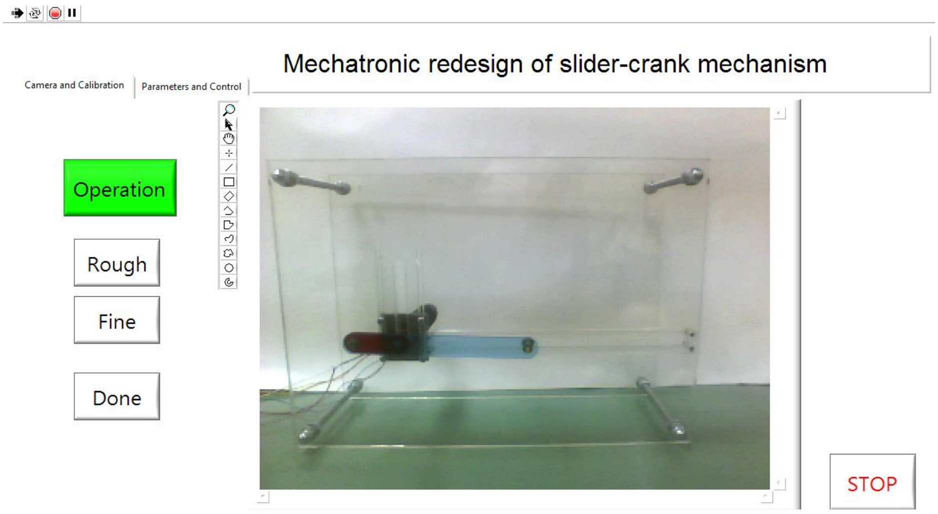

Fig. 7 Calibration mode with inner limit position of mechatronic redesigned slider-crank mechanism as starting position

After setup of all parameters and the calibration of the starting position, it is possible to run the experiment by pressing the **Operation** button, which will put the mechatronic redesigned slider-crank mechanism into the operation mode which is shown in Fig. 8. If some additional calibration is needed, then it is possible to go back to the calibration mode by pressing the **Calibration** button (Fig. 8).

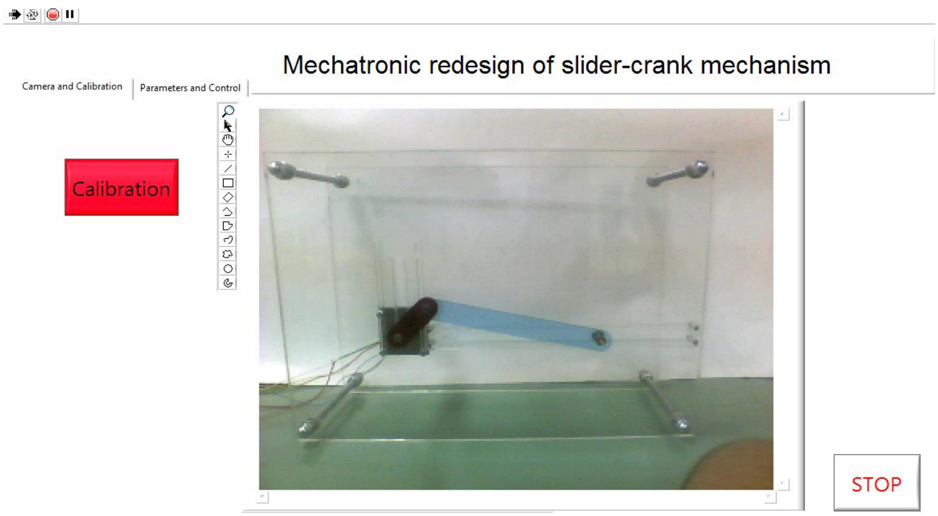

Fig. 8 Operation mode of mechatronic redesigned slider-crank mechanism

For testing of the control algorithm, the next example has been chosen for defining the desired velocity profile of the slider: the time that the slider remains in the initial position is, t_1=2 s, the time of the slider motion in one direction (the operating motion) t_2=5 s, the time of the slider rests after the operation motion t_3=1 s, the time of the slider motion in the other direction (the return motion) t_4=3 s and the time of acceleration and deceleration of the slider t_u=0.5 s, in accordance with Fig. 4. These times are chosen to be slightly longer, so that the user can notice the change in velocity of the crank in order to achieve the desired motion of the slider. The red graph in Fig. 9 shows the velocity of the slider calculated from the crank position which is measured by the optical encoder during the experiment, and the blue graph represents velocity reference. It can be noticed from the graph that the velocity of the slider corresponds to the defined velocity pattern.

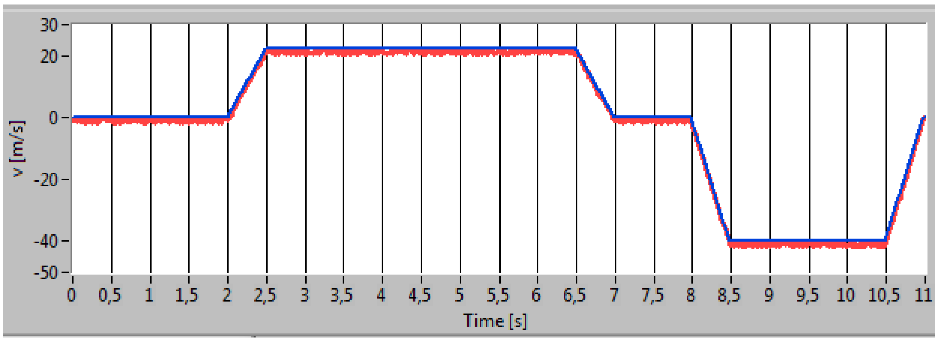

Fig. 9 Measured velocity of slider obtained during running of experiment

This experiment can be started remotely from a computer connected to the Internet using an Internet browser. All the necessary software for running the experiment remotely is installed on the server computer at the Mechatronic Laboratory of Faculty of Mechanical Engineering of University of Niš, Serbia, and there is no need for the remote user to do additional installations or settings. Thanks to the web camera it is possible to track the motion of the mechanism. This is a huge advantage of this kind of remote experiments because research studies from other institutions all over the world can use it to test their control algorithms without building the whole experimental setup. Interested in testing this remote experiment can contact the corresponding author *via* e-mail, for detail instructions about how to access to the experiment.

6. CONCLUSION

In this paper a mechatronic redesigned approach is presented on a representative example of a centric slider-crank mechanism. It has been chosen because the working and the return stroke of the slider have the same duration, so that if an application requires a mechanism with a slower working stroke, and, at the same time, the rapid return stroke the traditional approach requires the complete redesign of the mechanism structure. Using a servo DC motor, encoder, corresponding electronics, acquisition devices and appropriate software, as recognizable components of mechatronic systems, it has been shown that it is enabled to achieve a desired profile of the slider velocity, without changes of the basic structure of the slider-crank mechanism. For that purpose, a PID controller is used as a control algorithm, where the input into the controller is the error represented as the difference between the desired velocity and the estimated current velocity of the slider, and the output from the controller is a duty cycle of the PWM signal for the motor voltage supply. Testing of the proposed approach has confirmed that the measured velocity of the slider obtained during running of the experiment corresponds to the defined velocity of the slider. This mechatronic approach enables an expanded usage of traditional mechanisms in many other applications only by adjusting control parameters, without making mechanical changes of the basic structures of mechanisms.

Since the mechatronic approach of redesigning mechanical assemblies' opens possibilities for remote controlling over the Internet, the mechatronic redesigned slider-crank mechanism is developed as a remote laboratory experiment stationed at the Mechatronic Laboratory of Faculty of Mechanical Engineering of University of Niš, Serbia. For the remote purpose, it is firstly necessary to set the parameters and calibrate the mechanism into the starting position, and then, over live video streaming by a web camera, the mechanism motion can be tracked. The control algorithm, as well as remote access and live video streaming, is developed by NI LabVIEW software. Moreover, the remote control of the experiment enables the testing of the different control parameters to many research studies by simply visiting the web page of the experiment.

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