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Motion control of several electric actuators

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Abstract. Modern day industrial solutions in the field of electric actuators, often integrate the actuators with sensors and control units. This integration creates complex mechatronic devices. The complexity of these devices is evident, because this integration asks for communication between sensors, actuators and their control units, and also communication with external control units and sensors, as well as other actuators. This integration of sensors, actuators, control units and communication technologies is nowadays often referred to as Industry 4.0, which is a collective term embracing a number of contemporary automation, data exchange and manufacturing technologies and is a facilitation of the vision and execution of a "Smart Factory". This research deals with the problem of synchronizing nine electric actuators with integrated control units, which are controlled by an external control unit, while communicating through EtherCAT communication protocol. The problem is discussed by presenting a case study.

Keywords: industry 4.0; mechatronics; electric actuators; control;

1 Introduction

Today's industry is changing, both in conception and organization. Previously, the third industrial revolution introduced advanced electronics and information technology, which resulted in further automation of existing production processes. Nowadays, the development and establishment of global networks incorporate the machinery, warehousing systems and production facilities in the shape of Cyber-Physical-Systems. In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage, supply chain and life cycle management.

The Smart Factories that are already beginning to appear employ a completely new approach to production. Smart products are uniquely identifiable, may be located at all times and know their own history, current status and alternative routes to achieving their target state [1]. This business approach is named Industry 4.0, which is a term publicly known from 2011, and includes six design principles [2]:

- Interoperability;
- Virtualization;
- Decentralization;
- Real-Time Capability;
- Service Orientation;
- Modularity.

Interoperability means that all Cyber-Physical-Systems are able to communicate with each other, and are connected over to Internet of Things and Internet of Services in the context of SmartFactory [3]. Virtualization means that a virtual copy of the physical world allows the monitoring of the processes [4]. Decentralization as a demand, which arises due to increasing difficulties to control systems centrally, makes it necessary to keep track of the whole system at any time [5]. To be able to keep track of the whole system at any time, real-time capability is required [5]. To be able to answer to specific customer requirements, service orientation is needed as well [5]. Finally, modularity as an approach enables flexibility regarding to the adaptation of changing requirements by providing functional independency of individual modules [5][6].

Modern mechatronic devices are gaining more ground in most diverse areas [7]. Large number of devices contain more and more mechatronic elements [8]. These devices also have multiple sensors and actuators.

The most widely used actuators are rotating motors. The development of direct current (DC) electric actuators, which do not use commutators with brushes for current commutation, resulted in changes in the design of DC motors [9]. While the electronic commutation requires electronic components to be able to run the motor, it also allows the control of the motion characteristic of the electric motor. The motors which are presented in the case study are the Dunkermotoren BG 45 range of brushless, direct current motors with integrated EtherCAT communication interface [9]. These motors can be combined with control electronics, gearboxes, and encoders in a modular system to provide a flexible, adaptable, market-oriented solution.

Usually rotational motion is converted to linear motion, or the well-known pneumatic/hydraulic systems are used for linear motion. These solutions usually offer a simple and cheap way to achieve the linear motion with good precision and performance. However, there are multiple different options to achieve linear movement. Among these, linear motors are starting to appear as a potential option for solving the problem of linear motion. The linear motor's characteristics are similar to the conventional systems, but this system has additional positive attributes, which makes it a desirable solution.

There are different types of linear motors, including step by step, DC, AC induction, iron cored and ironless brushless DC linear motors, and tubular linear motors [10].

The linear motor used in this research is a tubular linear motor. This type of linear motor is created when the regular BLDC motor is unfolded, and then folded back along the line, which is perpendicular to the magnetic field's spreading direction [11][12]. It can be made with short and long coils, but since the long coils are expensive to make the shorter coils are more common. The moving part is usually a long tube, which has neodymium magnets in it with alternating polarities.

If the motor has to work in conditions, which require high precision positioning, an external encoder has to be included. Typically the working force is around 600N. It can achieve 20G acceleration up to 5 m/s velocity [13][14]. The repetition precision is 0.05μm, and the gap is less than 0.5 mm. The motors which are presented in the case study are the Dunkermotoren Servo Tube STA1104-1116 linear motors and Sx2504-2510 linear modules [11].

The presented research deals with the problem of simultaneous control of three groups of electric motors. One group consists of three motors, one SM2504-868 and two STA1104-116. The second group consists of three motors as well, one SM2504-868 and two BG45EC. The third group consists of three motors too, two STA1104-116 and one BG45EC-PLG42s, which is equipped with a planetary gearbox. All motors are mounted on the mechatronic exhibition device developed for a company, which produces the actuators. The basic goal of control is to achieve synchronous and appealing movement of the motors having in mind the motors' properties regarding position, velocity and acceleration [9][11]. This structure presents a possible constituent of a Smart Factory.

The reminder of the paper is structured as follows: In the 2nd paragraph the developed mechatronic device is presented in brief. Also, the structure of the system of electric actuators, control unit, and auxiliary components which form the mechatronic system is introduced. Following that, the 3rd paragraph presents the control algorithm and the motion characteristics of all actuators in the case study. Conclusions are given in the 4th paragraph.

2 The developed mechatronic device

One of the leading companies in the field of advanced motion solutions and automation, required a mechatronic device, which would be a popular and useful form of presentation for the company at exhibitions. In order to be able to design such a device several functional requirements had to be fulfilled. The main functional requirements are presented in 1. Table.

1. Table Main functional requirements

Ensure attracting the attention of visitors of the exhibitions
Provide easy handling (by the visitor)
Provide automated operation mode
Include appropriate security measures
Provide full functionality (according to the suggested solution)
Set the maximum width and length, taking into account the dimensions given by the company
Set the height, taking into account the average height of a human
Enable multiple assembling and disassembly of all parts
Minimize the use of machined parts
Provide appropriate guidance and embedding
Provide easy maintenance
Embed the company’s brushless DC-motors
Embed the company’s linear motors and actuators - series ST
Maximize speed (by taking into account the characteristics of the drives)
Maximize acceleration (by taking into account the characteristics of the drives
Maximize the visibility of embedded products of the company
Minimize the visibility of auxiliary parts

2.1 The structure of the mechatronic device

Based on the defined functional requirements, a mechatronic device is developed, which fulfills all requirements. The device is a table tennis ball shooting device. The table tennis ball has a printed logo of the company and it serves as a gift to the visitor if the visitor is able to “win” it. To be able to “win” the ball, the visitor navigates the shooting device and tries to avoid two complex moving obstacles, by shooting the table tennis ball between the obstacles. If there are no visitors who are willing to play, the device runs in automated mode. The model of the developed mechatronic device and the actual device are presented in **Fig. 1**. The device consists of several subassemblies:

- Energy supply subassembly. This subassembly supplies the required electric energy for the control units, the sensors and the actuators;

- Control unit subassembly. This subassembly enables the control of the device for two modes of operation (manual and automatic);
- Frame subassembly;
- Ball feeder subassembly. This subassembly enables the storage of approximately 100 table tennis balls, and the gravitational feeding of the dispenser subassembly. It also consists of the disused and won table tennis balls' containers;
- Ball dispenser subassembly. This subassembly feeds the launcher subassembly, by launching the table tennis ball simulating a projectile motion;
- Ball launcher subassembly. This subassembly constantly rotates for a predefined angle around an axis that is perpendicular to the xy plane of the local coordinate system od the device. It also allows the shooting of the table tennis ball;
- First obstacle subassembly. This subassembly has a function to prevent the passing of the table tennis ball;
- Second obstacle subassembly. This subassembly has a function to prevent the passing of the table tennis ball.

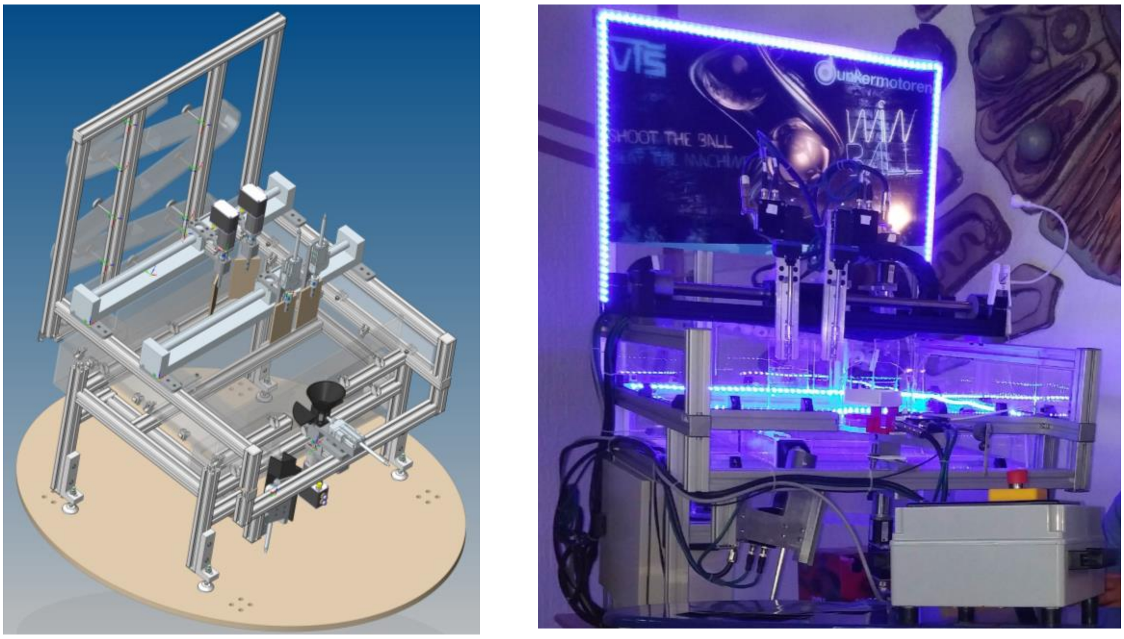

Fig. 1. Developed mechatronic device

2.2 The structure of the system's components

The structure of the system is presented in **Fig. 2**. It consists of the PLC, nine electric motors and two sensors.

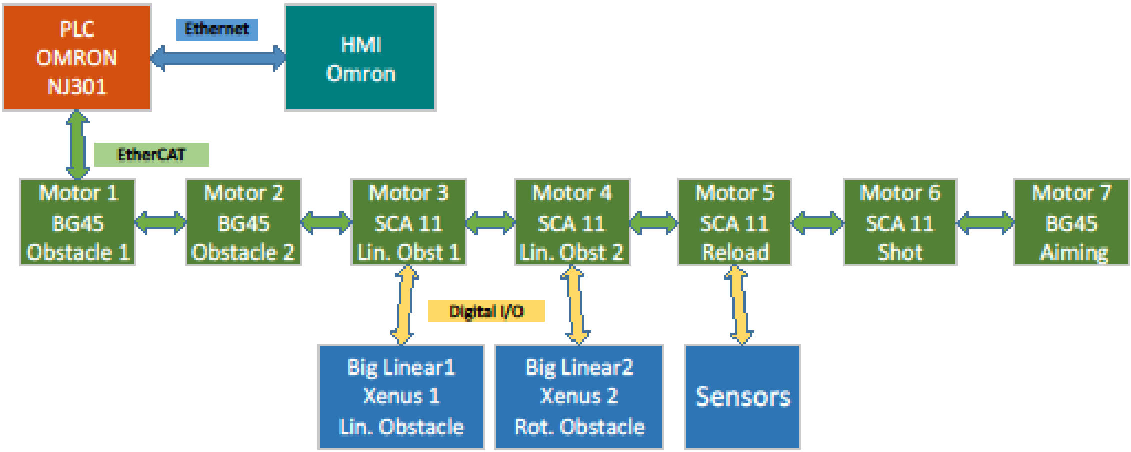

Fig. 2. System structure with PLC nine motors and two sensors

In **Fig. 3**, the first group of motors is presented, which consists of one SM2504-868 (BigLinear1) and two STA1104-116 (Motor3 and Motor4) motors. In **Fig. 4**, the second group of motors is presented, which consists of one SM2504-868 (BigLinear2) and two BG45EC (Motor1 and Motor2) motors, while in **Fig. 5**, the third group of motors is presented, which consists of two STA1104-116 (Motor5 and Motor6), and one BG45EC-plg42S (Motor7) motors.

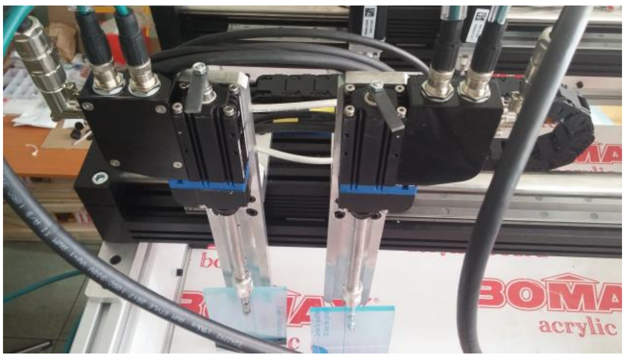

Fig. 3. First group of motors

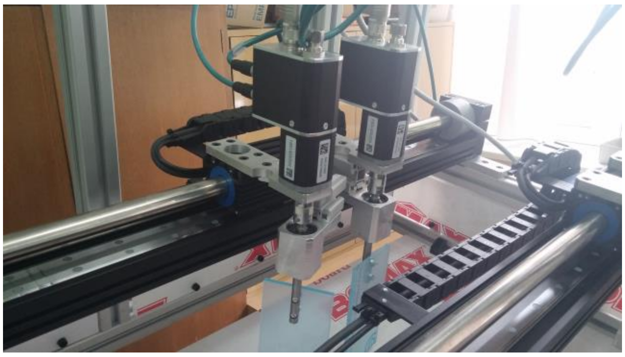

Fig. 4. Second group of motors

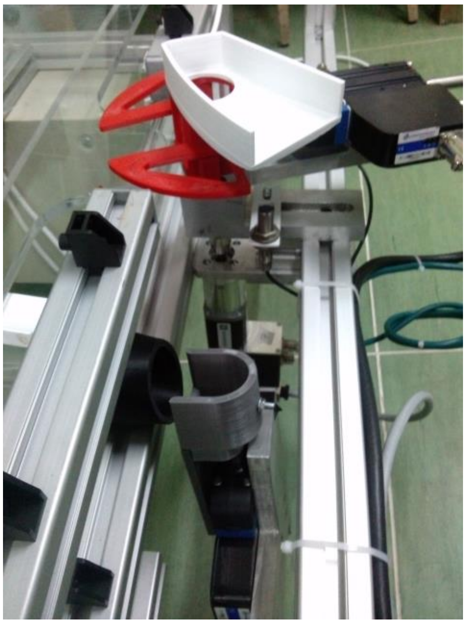

Fig. 5. Third group of motors

3 Case study

The case study is structured as follows. First, the control algorithm which controls the device is presented. Following that, the kinematics of the motors is presented.

3.1 Control algorithm

The control algorithm is presented in **Fig. 6**. It allows automatic and manual mode of operation. The functions, which are called during execution are special subroutines. They control the motion of each motors. Due to the complexity of the subroutines, they are jus listed in 2. Table.

2. Table Main functional requirements

Function name	**Motor**	**Movement**
Homing_BigLinear1	BigLinear1	Homing
Homing_BigLinear2	BigLinear2	Homing
Homing_LinearShoot	Motor6	Homing
Homing_RotaryAiming	Motor7	Homing
Motion_RotaryObstacle1	Motor1	Rotation
Motion_RotaryObstacle2	Motor2	Rotation
Motion_LinearObstacle1	Motor3	Linear
Motion_LinearObstacle2	Motor2	Linear
Motion_BigLinear1	BigLinear1	Linear
Motion_BigLinear2	BigLinear2	Linear
Motion_RotaryAiming	Motor7	Rotation
Motion_LinearReload	Motor5	Linear
Reload_RotaryAiming	Motor7	Rotation
Motion_LinearShoot	Motor6	Linear

3.2 Motion characteristics of the actuators

To be able to fulfill all functional requirements defined by the company, the overall motion of the electric actuators has to be dynamic, synchronous and appealing. The dynamic motion effect is especially required for the first and second group of actuators, because these actuators should present the motion possibilities of the actuators, while the third group has to perform synchronized motion as well. The appealing effect should be present at all motions. Of course, synchronization of the motors in the first and second group ads to the overall impression. Therefore different motion patterns are defined for all groups of actuators.

Fig. 6. Control algorithm

The first group of motors has to perform a dynamic and synchronous motion, which results in an elliptical motion of the ends of the vertical motors' rods (**Fig. 7**).

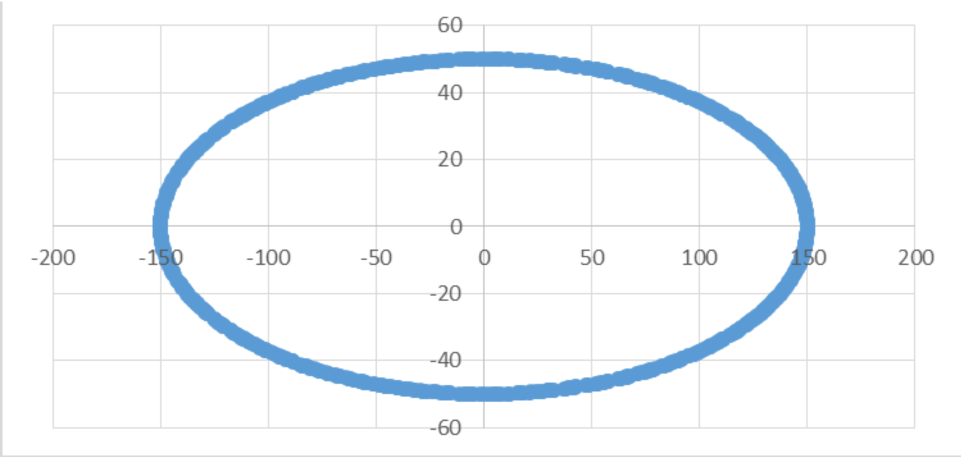

Fig. 7. Relative positions of the ends of the vertical motors' rods

Additionally, the first vertical motor's rod should perform clockwise elliptical motion, while the other vertical motor's rod should perform counterclockwise elliptical motion. To achieve this, the horizontal motor and the vertical motors have to move in synchronized sinusoidal trajectories during time. Detailed information regarding positions, velocities and accelerations are discussed in [15][16]. The motors' motion sequence is repeated in every 8 seconds, and is presented in **Fig. 8**, **Fig. 9**, and **Fig. 10**.

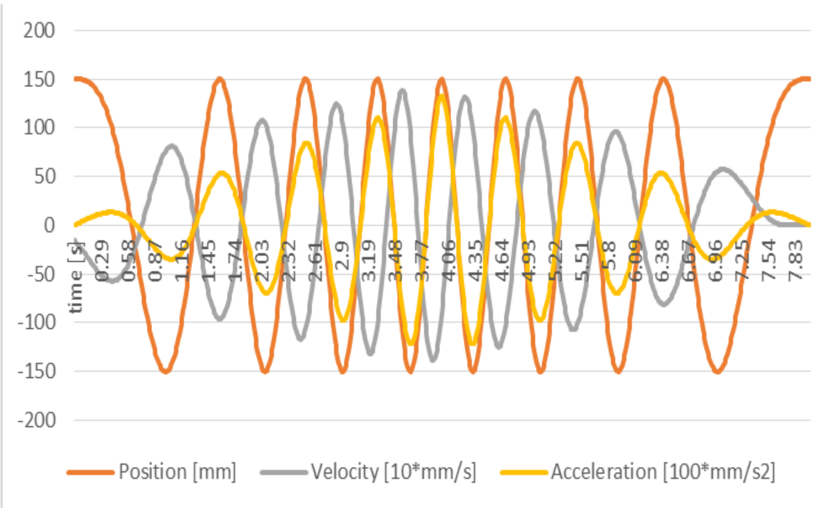

Fig. 8. The motion of the horizontal motor

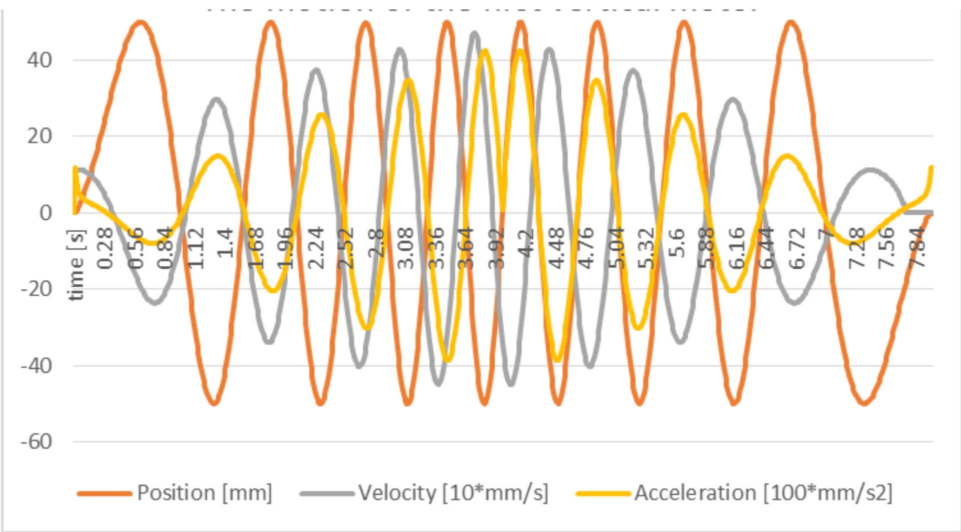

Fig. 9. The motion of the first vertical motor

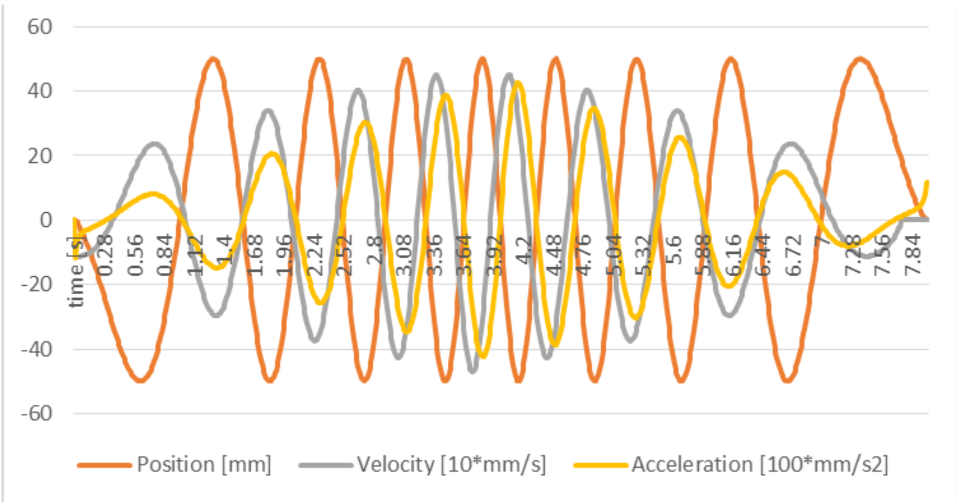

Fig. 10. The motion of the second vertical motor

This definition of movement allows the clockwise, i.e. the counterclockwise elliptical motion of the vertical motors' rod ends (**Fig. 11**).

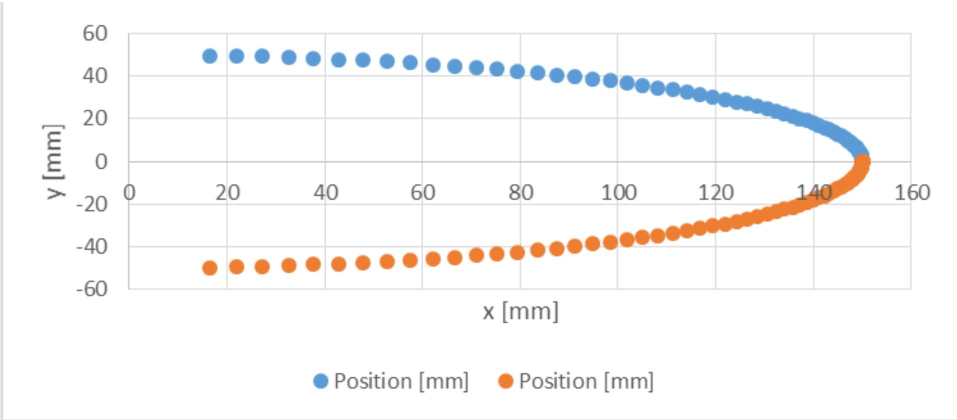

Fig. 11. Relative positions of the two vertical motors' rods end during first 0.6 [s] (blue – first motor, red – second motor)

The second group of motors has to perform dynamic and synchronous motion too. The horizontal motor's motion sequence is repeated in every 8 seconds, while the rotational motors' motion sequences are repeated in every 16 seconds. Detailed description of the motors' motion can be found in [15][16].

The motion of the horizontal motor is presented in **Fig. 12**.

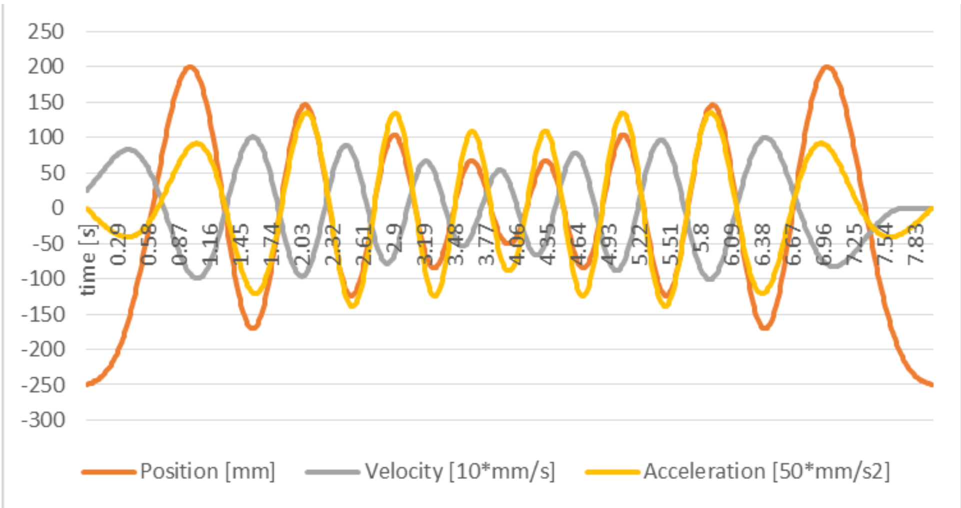

Fig. 12. The motion of the horizontal motor

The motion of the rotational motors is presented in **Fig. 13**, and **Fig. 14**., where one increment (inc) equals 1/1024 of one full rotation.

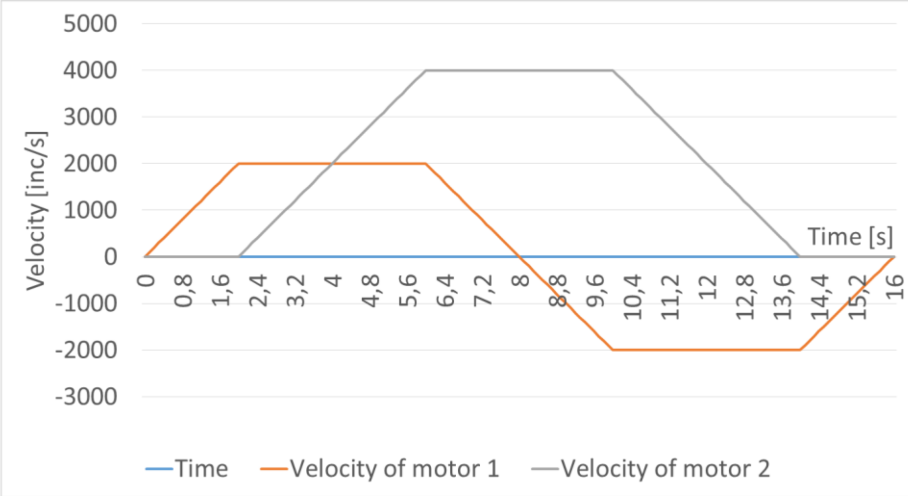

Fig. 13. Velocities of rotational motors

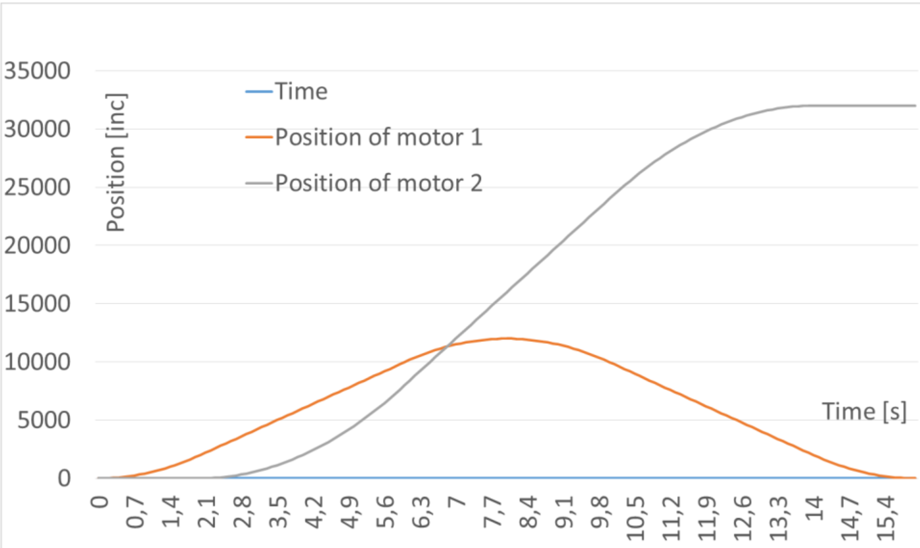

Fig. 14. The positions of the rotational motors

The basic functional requirement in the case of the third group of motors is to secure the loading, aiming and shooting. Therefore, the linear motors which are used for loading and shooting are programed in a way, which allows the fastest moving possible. This is secured by setting the acceleration and velocity to maximum values defined by the producer [11]. The positions of the motors are based on maximum values for acceleration and velocity. The rotational aiming motor's velocity and position in time is presented in Fig. 15. The acceleration of the motor is presented in 3. Table.

3. Table Acceleration of the rotational aiming motor

Acceleration aiming motor [inc/s2]	absolute start time [s]	absolut e end time [s]	relative start time [s]	relative end time [s]
200	0	1	0	1
0	1	3	0	2
-200	3	5	0	2
0	5	7	0	2
200	7	8	0	1

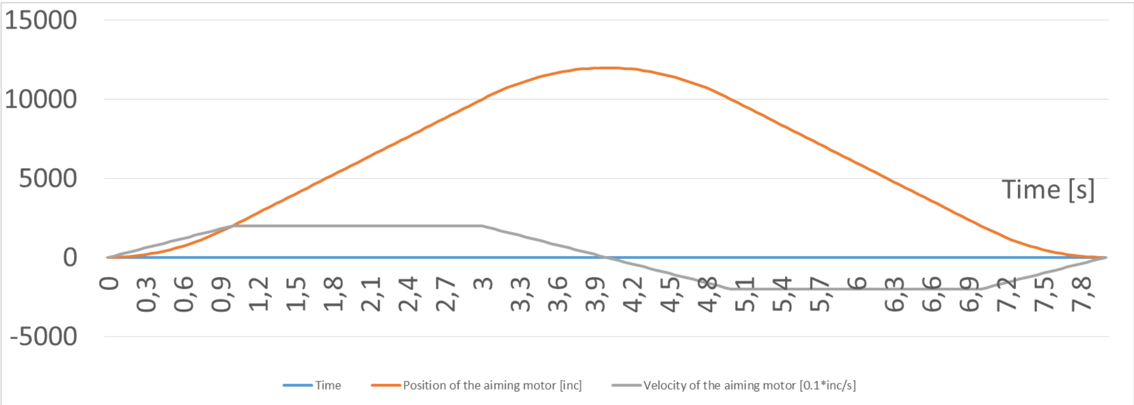

Fig. 15. Position and velocity of the rotational aiming motor

4 Conclusions

The ongoing change in industry conception and organization through the establishment of global networks resulted in the creation of Cyber Physical Systems. In the manufacturing environment, these Cyber-Physical Systems comprise among others smart machines, which are capable of autonomously exchanging information, triggering actions and controlling each other independently.

The presented research dealt with the problem of simultaneous control of nine electric motors. The basic goal of control was to achieve synchronous and appealing overall movement of the motors having in mind the motors’ properties regarding position, velocity and acceleration. This was achieved by creating a device, which was basically a game for visitors who attend fairs. It was able to shoot table tennis balls either automatically or by the visitors.

The electric motors were controlled by predefined functions. The result of the case study showed that the presented mechatronic system could have worked properly with the given structure, which is a good starting point towards designing more complex mechatronic systems.

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