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Applying Graphical Representation Method in Teaching Mechatronics Problems in Industrial Automation to Undergraduates – A Case Study*

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Industrial automation engineers need a detailed knowledge of the mechanical system of the machines when they program and implement complex motion control functionalities on machines. However, there are no information standards to support the conceptual design of a new machine with all relevant data required for both mechanical and motion control views. As an academic consequence, programming exercises and lessons lose linkage with the mechanical specification, and the experience of students is more focused on the automation perspective. Therefore, the authors have proposed a new intermediate information representation system between mechanics and logic representations: "Mechanical and Motion Control Schematics" or MMCS, which may serve as a support for the teaching of advanced programming of motion control functionalities of machines. The paper addresses the hypothesis of whether the use of MMCS improves the communication and understanding of advanced concepts of movements when compared to mechanical drawings. To assess its usefulness, an experiment presented in this article was designed and performed. Two groups of students carried out a timed test with identical exercises varying only the mechanical documentation used. One group used the standard mechanical drawings as a reference, and the other group used the mechatronic drawings presented in this article. The experiment results show that MMCS provides benefits in reducing time and a better understanding and strengthening of advanced concepts of motion control.

Keywords: academic support; engineering education; industrial automation engineering; mechatronics; multidisciplinary design; practice test

1. Introduction

Industrial machinery designers are making widespread use of servo drive technology [1] with new automation software resources in order to meet the flexibility and performance requirements demanded from factories [2]. These resources are the support for a machines mechatronic implementation approach, where logic or programmed solutions are used to implement functionalities that would have been done with mechanical elements in a more traditional machine configuration. Where there used to be a single driven axis hard-coupled to a variety of mechanical transmissions and gears, there are now several servo axes working synchronously through electronic and dynamic relations (gears, cams, etc.) [3]. This translation of the motion relations from the physical world to the virtual/logic one, introduces new concepts such as virtual axes, electronic gearing between real and virtual axes, etc. in the machine design activity [4] and engineering education programs should support students in adapting to these new technological resources [5].

Despite this new mechatronic interdisciplinary approach, both educational branches (mechanical and automation), mainly continue to work with their own modelling and designing technologies. Standard graphical information representation methods are highly oriented towards the data that are more relevant for each technology. That sometimes makes it difficult to understand the data from the other technological point of view, either because the data are scarce as they do not take into account relevant information for the other view, or because students with different profiles (mechanical and automation) are not used to the principles and information representation conventions of the other technology.

No representation system has been found that collects and expresses together the relevant common information of mechanics and motion control. This is presented in the state-of-the-art review (Section 2), and it has two consequences. The first one is that it is often difficult for industrial automation engineering students to deduce the values of parameters needed to configure the motion commands from mechanical drawings. Much of the mechanical data is unnecessary for the programmer. The second consequence emphasizes the difficulty to represent movements of parts and other essential software resources such as virtual axes, electronic gears, etc. There is no systematic approach for doing that despite the direct influence that those resources have on the mechanical system.

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Sometimes, in order to reinforce the understanding of such concepts when presenting mechatronic machine automation exercises and problems to students, informal schematic drawings have been used. These "freestyle" representation methods and graphics, although useful, valid and almost self-explanatory most of the time, are not systematic. For the same problem, there may be as many different representations as users. They do not follow any specific methodology and they do not use either a common information model or graphical symbols repository.

Therefore, the authors of this paper have proposed a new intermediate information representation between mechanical and electronic/logic representation: "Mechanical and Motion Control Schematics" or MMCS. It defines a systematic approach for obtaining intermediate drawings using a set of symbols to express mechanical elements relevant for the automation view and for the new software resources (virtual axes, synchronize movements, etc.). The MMCS main characteristics are explained in more detail in Section 3.

In this way, it is intended to obtain the same result regardless of the person who will perform them. Besides, another advantage is that the students can recover the mechanical information from a simplified mechanical document, which is systematically generated from a blueprint.

The paper addresses the hypothesis of whether the use of MMCS (or a similar intermediate information representation method between mechanic and electronic/logic designs), may reduce the time needed for obtaining mechanical information and improve the understanding and communications of advanced mechatronic motion control functionalities compared to mechanical drawings.

A comparative experiment, which is described in Section 4, was performed to evaluate the differences between the use of mechanical drawings and MMCS to obtain the values of mechanical parameters needed to code motion commands. Section 5 contains the results of the experiment. They validate the hypothesis as the students who had used MMCS spent less time and achieved more correct answers in the whole experiment than the other group of students using just pure classical mechanical drawings. The benefits that MMCS provides in reducing time and, above all, strengthening the understanding and communication of advanced concepts of motion control. This is discussed in the conclusions in Section 6.

2. Information Description Methods for Machine Design

Each engineering branch tends to use its own information modelling conventions to communicate and design, and different graphic representation systems are used in each knowledge area (electrics, mechanics, automation). However, they are not often deeply considered into the automation and programming curriculums, at least not beyond the basic technical drawing concepts within the first years of their Bachelor degree [6]. The following subsections introduce the main modelling methods for representing machine motion information used by mechanical and industrial automation students.

2.1 Description Methods for Machine Mechanics

From a mechanical point of view, kinematic schemes, mechanical drawings and technical documentations cover most of the technical descriptions of machines with servo axes. Mechanical blueprints usually focus on specific details to manufacture or assemble parts of a machine: manufacturing tolerances, surface roughness, etc. Standards exist such as ISO 128 [7] for general and basic principles to represent lines, views, cuts and sections, ISO 2768 [8] for the representation of manufacturing processes tolerances, or ISO 2203 [9], which is applied to represent elements of servo axis kinematic chains, such as gearboxes. These engineering drawing standards are widely used and are found in scientific literature, technical documentation and mechanical courses in industrial automation engineering programs.

Most mechanical drawing representations show the elements in a static position, without taking into account the movement of the machine or the relative movements of the parts. Reference systems and data to describe the movements are not explicitly identified. Finally, the understanding of the machine movements relies on the reader's interpretation of the drawing.

ISO 3952 [10] provides a simplified representation of rigid bodies where the mobile parts and the mechanical mobile relationships between them are identified. This standard provides a better understanding of the machine movements avoiding detailed mechanical information. However, it is still focused on documenting specific mechanical information and much of the information represented is irrelevant for the automation and motion control point of view, for instance, kinematic pairs of the joints.

Despite the extent of the mechanical information in these types of representations, other important information is difficult for the automation student to extract; for instance, the information of an axis stroke and the point that will act as the reference for the movements control. Moreover, although mechanical standards deal with kinematics and system dynamics, temporal and electronic virtual links between mobile parts implemented in modern mechatronic control systems are not addressed.

When it comes to representing the movements of the machine, different non-standard solutions are also found in the literature. A simplified type of representation can be found in [11–13] where the movements of the axes are described with sketches and labels. Others use arrows and labels on 3D images generated by CAD [14, 15], or over pictures of real machines [16, 17] to try to describe how they work. However, all of these examples are case specific.

2.2 Description Methods for Machine Automation

The sequences of movements are described by instructions defined by programming languages. There are numerous solutions to implement and describe the operation of machines using those languages. Some standards are specialized in the programming of a certain type of machine, such as CNC machines with the ISO 6983 standard [18]. ISO 6983 defines the machining toolpaths using text commands to create the motion sequence for manufacturing a specific part. Given their wide use in the manufacturing and 3D printing industry, automation students are also trained in the programming of these systems [19]. More general-purpose automation standards such as IEC 61131-3 [20] and PLCopen [21] are supported by PLCs (Program Logic Controllers) and NCs (Numerical Controllers). They are the choice when automating custom or more specific mechatronic machines. In fact, main PLCs manufactures have chosen PLCopen as the programming framework of their devices [22] and therefore, a range of educational institutes use it in their training courses and research activities [23]. PLCopen provides a set of resources for programming motion control applications involving servo axes. More specifically, PLCopen Motion Control specification defines an automation framework based on standard Function Blocks to implement axes movements with three complexity levels. The first, discrete or PTP (point to point), automates the isolated movement of an axis (see Fig. 1a). The second, coordinated, is when two or more axes move to perform complex paths through interpolation commands working as a group in Cartesian or other kinematics (see Fig. 1b). And the third, synchronized, is when the movement of a slave axis is conditioned by the movement of another axis acting as a master, (see Fig. 1c).

PLCopen for Motion Control specification also defines new logic resources, such as virtual axes, which are logical axes that are not linked to a physical servo axis. Moreover, electronic relationships between real and virtual axes (e-gears and e-cams) replace their mechanical equivalent. Nevertheless, these virtual and electronic relations are not included in mechanical documentation and motion control information models despite their significance in the operation of a machine.

In this context, engineering students need to know the expected axes movements and future axes relations, including any virtual or logic elements involved. These "logic relations" interpretations are not easily inferred from "motion control" logic, even if there were a conceptual representation of the logic structure or algorithm. Logic contains a lot of irrelevant information for mechanics, such as many variables, data types, etc. Furthermore, this logic is documented by graphical representations more oriented to event sequences specifications, where time is a relevant variable, rather than to the machine static configuration, such as IEC Standard 60848 (GRAFCET/SFC) [24] or Petri Nets [25]. Both standards are also present into industrial automation engineering programs [19, 26].

Additionally, non-standard approaches can be found in the scientific literature and documentation provided by automation device manufacturers. They often use non-standard representations and graphic tools for kinematic chain sizing, commis-

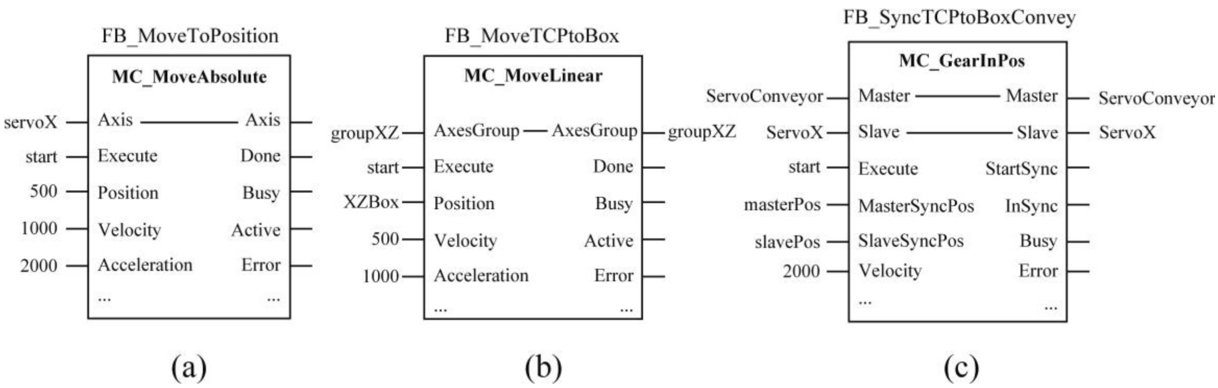

Fig. 1. Examples of the use of function blocks. (a) Discrete movement of an axis (b) Coordinated movement of a group of axes (c) Activation of an electronic gear between two axes.

sioning and simulation or monitoring [27–29]. Although they provide a "conceptual" mechatronic view of the machine, they are not directly linked with the mechanical designs, and they do not represent a systematic and universal approach for an intermediate representation of the machine.

3. Mechanical and Motion Control Schematics

There is no standard or broadly recognized method to graphically represent industrial mechatronic configurations considering all relevant mechanical and motion control information. Both professional and student profiles (mechanical and automation engineers) have their own design frameworks, oriented to their own technologies but without systematically considering all relevant information for the other.

MMCS is intended to fill this empty common space by formalizing a set of symbols and representation methodology to complement explanations to students and academic activities. This new representation system can be seen as a combination of simplified mechanical drawings and kinematic diagrams but with additional motion control graphical information. The rest of this section describes the set of main symbols used to create an MMCS drawing. They have been divided into two parts: one for mechanics and one for motion.

3.1 Representation of Mechanics

From an automation student viewpoint, it is important to clearly distinguish structural elements and moving elements to be controlled by logic commands. MMCS proposes a representation convention for this purpose. It is detailed below.

3.1.1 Structural Elements

The structure of the servo-driven elements has been simplified as much as possible, removing non-essential information from the programmer's point of view, such as data not directly involved in the movements, mechanical details such as tolerances, manufacturing finishes, etc. Structural elements are represented in MMCS with a striped pattern, as Fig. 2 shown. However, it is important to keep the proportions and overall shapes present in the mechanical drawings in order to be able to identify the main elements.

3.1.2 Servo-driven Kinematic Chain

MMCS represents only the elements of the specific servo-driven kinematic chains that are controlled from a motion control command in the automation application. Non active parts such as mechanical gears, mechanical couplings, etc., are avoided. For instance, for the case of servo-driven belts (Fig. 3), the linear position of the moving carriage is relevant for the automation application, but not the angular position of the servomotor rotor that moves the belt. That information is indeed relevant to the automation students in order to calculate the "scaling factor" during the mechatronic chain sizing and commissioning phases. The required data such as radius, number of teeth, etc., are already explicit in the mechanical design.

In this kind of linear configuration, the specific structural element working as the guideway for the moving carriage provides important information in terms of automation. It defines, for instance, the type of linear movement to be performed and its limits. Therefore, this guideway is explicitly considered in an MMCS sketch as a thick black line. Fig. 3 highlights this MMCS convention to represent mobile (guided) elements and guide elements of a servo-driven belt. It presents the MMCS for two types of linear servo-driven configurations. The 3D models do not explicitly detail the wide-range positions and maximum stroke of the belt. Guideway and guided elements may also miss being distinguished in some cases, and more than one 3D view, with the mobile element in different positions, would be needed to communicate this information.

However, just one view would be required using MMCS representation since it unequivocally identifies that information: mobile and guided elements and limits of the movement (Fig. 3a step 2 and Fig. 3b step 2). Nevertheless, Fig. 3 shows the maximum travel positions with three MMCS views to better illustrate the difference between left and right configurations. From top to bottom, Fig. 3 also shows the 3D views of two linear axes, the MMCS representation in its intermediate position (as in

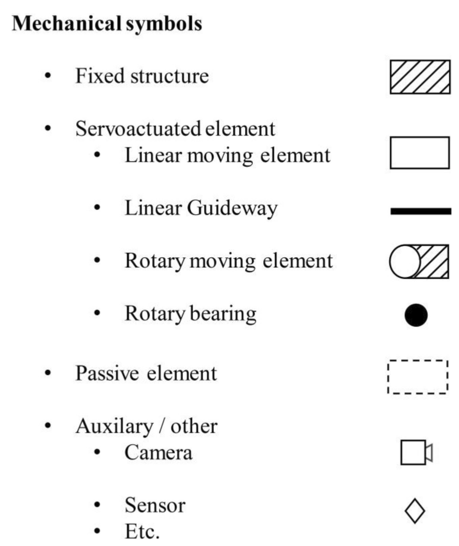

Fig. 2. Summary of the MMCS Mechanical symbols.

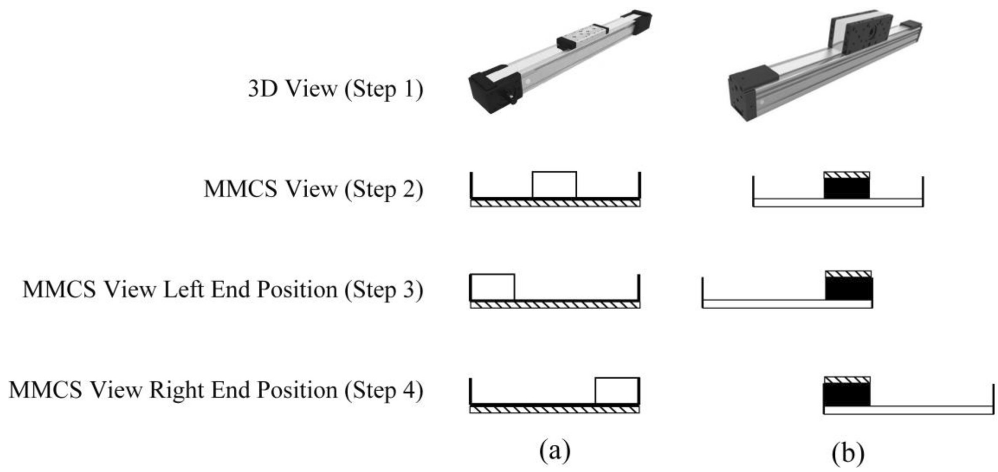

Fig. 3. Examples of a linear servo-driven axis. (a) The carriage is the moving element. (b) The carriage is the guided element.

the 3D model), the movement of the axes at the left end and finally (Fig. 3a step 3 and Fig. 3b step 3), at the right end (Fig. 3a step 4 and Fig. 3b step 4).

Fig. 2 summarizes some of the main graphic elements proposed in MMCS. For instance, dashed lines represent passive objects that temporary become part of the kinematic chains. In modern motion control applications, if a product is transported by a conveyor belt, it becomes a temporary virtual axis. For the rest of the "real axes" of the machine, especially for those that move a tool to perform work on the product, this virtual axis is the master for gearing in or in fly saw (fly work) operations.

Other types of non-servo-driven components such as cameras, sensors (represented by a diamond in Fig. 2) or even pneumatic cylinders can be included in the representation, although following the corresponding graphical standard [30].

3.2 *Representation of Movement*

Axes movements to perform trajectories of TCPs are commanded by PLC or NC controllers. Automation students need a specification of the process, in terms of movements and trajectories, as a requirements specification input to the automation solution design. Fig. 4 shows the three types of information related to movements and trajectories to be represented in an MMCS blueprint: coordinate systems, paths/trajectories, and type of movement.

3.2.1 Coordinate Elements

Several coordinate systems (CS) can coexist on the same machine. In addition to the usual ones such as machine CS, absolute CS, or Object CS, others can be added: CS for each servo axis, for the manipulated objects, and even for virtual axes whose trajectories are based on the real movements generated by inverse transforms.

Fig. 4a illustrates the set of symbols to represent the reference position points used to specify the movement of tools and effectors. They can be used for both linear and rotary motions, for real servo axes or virtual ones, and motions in one or several dimensions. Advanced sensors, such as machine

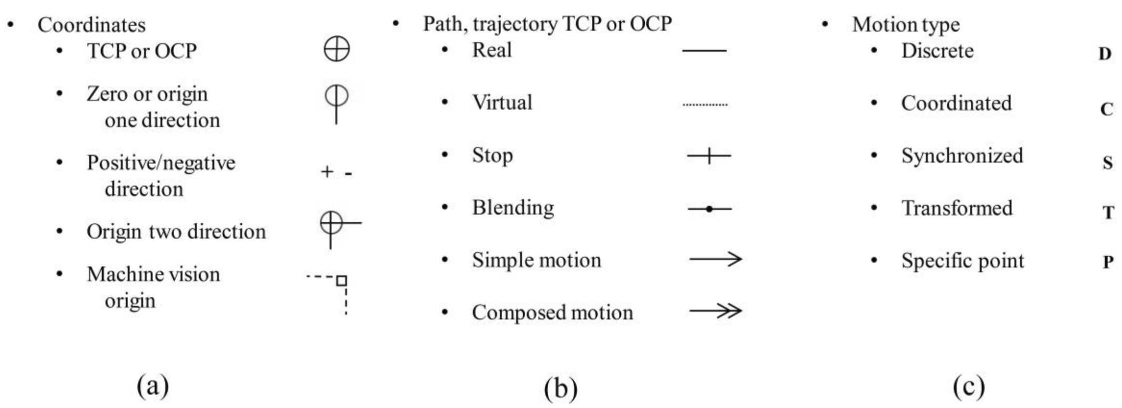

Fig. 4. Summary of the MMCS motion symbology. (a) Coordinates. (b) Path, trajectory TCP (Tool Centre Point) or OCP (Object Centre Point). (c) Motion type.

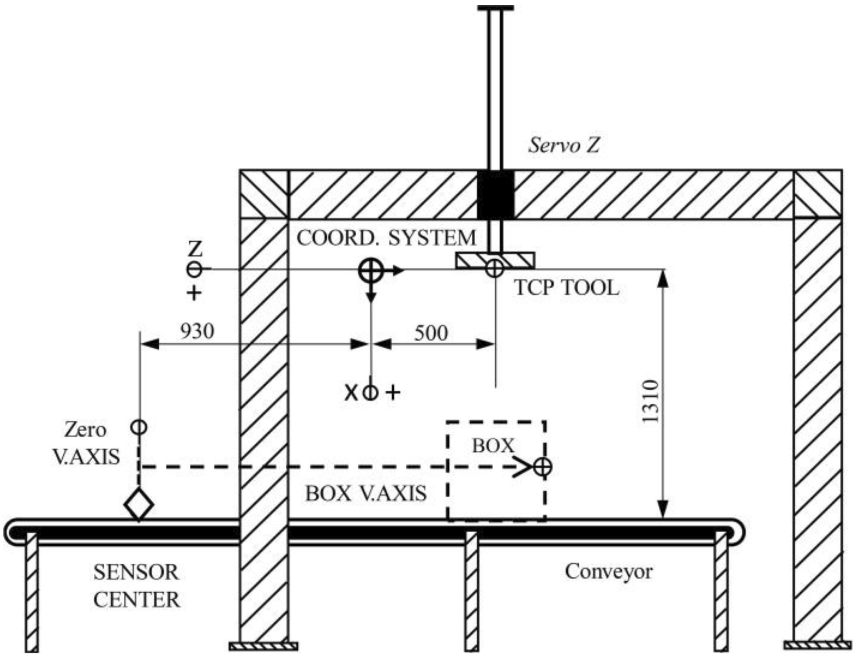

Fig. 5. MMCS drawing of a picking application.

vision systems, would need their coordinate systems.

The exact points to which the position is measured according to the corresponding coordinate system are represented by a cross inscribed in a circle, as shown in Fig. 4a and Fig. 5 ("TCP TOOL", "BOX" and "COORD. SYSTEM" labels). These conventions can be seen in the Fig. 5 MMCS example. It represents a machine that performs a picking operation to a box (represented by a virtual axis) that is moved by a conveyor belt. The servo axis identifier can be placed wherever convenient, typically close to the representation of the active element. In the case of a virtual axis, the letter "V" is used as a prefix, as the virtual axis "VAXIS" depicting the box in Fig. 5.

3.2.2 Path and Trajectory

Fig. 4b presents the MMCS symbols for paths and trajectories. TCP or OCP paths are drawn with a solid black line and dashed in the case of OCPs for virtual axes. An example of a virtual axis path can be seen in Fig. 5 (BOX Vaxis).

The tip of the arrow indicates the direction of motion. The arrow type is used to distinguish between direct movement (single arrow) and movements from a kinematic transformation or a combined movement (double arrow).

The stopping points are represented with a black line perpendicular to the path, and the points where different movement commands are concatenated (blending points) are represented with a black circle. Fig. 6 illustrates both situations.

3.2.3 Type of Movement

The type of a movement can also be specified by a representative letter followed by a number to identify the sequence step in a composed movement. The types of motion considered are: discrete (D), coordinated (C), synchronised (S) or transformed (T), as shown in Fig. 4c. Synchronized and transformed axes need a master axis to be specified, together with a relationship pattern between both: gear in coupling factors, cam definition, or the specific kinematic transformation. The letter "P" is used to represent an exact point in the trajectory, such as a control point or an end-point of a movement. Fig. 7 contains added information about the type of movement in the Fig. 6 trajectories. The left trajectory (represented in Fig. 7a) describes two discrete motions with intermediate stop. The tra-

Fig. 6. Examples of different type of path. (a) Simple real TCP path (b) Simple virtual TCP path.

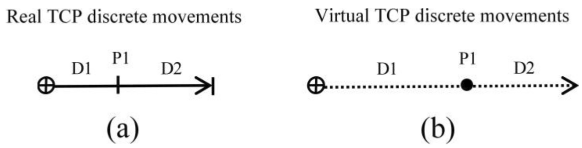

Fig. 7. Examples of different type of movements. (a) Simple real TCP discrete movements. (b) Simple virtual TCP discrete movements.

jectory on the right (Fig. 7b), is a virtual axis performing two blended motions.

If the individual movements of two or more servo axes jointly affect a TCP path, each contribution is indicated separately by a comma, except for the case of coordinated movements, where all axes work together as a group and the movements is ruled by interpolation functions. For example, if a horizontal axis is synchronized with a slave axis (a box) while a vertical axis descends with a discrete movement to perform a picking operation, it would be noted as "S1, D1".

4. Experiment

An experiment was designed to validate the advantages of using MMCS drawings. This experiment was performed with industrial automation engineering students. The aim of the experiment is to validate the hypothesis which states that the use of MMCS for teaching improves both the results in understanding and the time spent by the students to solve motion control exercises based on real machinery, using PLCopen electronic resources for programming.

Students had to parameterize the movement programming instructions from the mechanical documentation supplied in two different situations: one with only mechanical drawings and the other with only MMCS drawings. Both types of drawings serve as a basis for obtaining values to parameterize movement instructions, for example, distances to be covered by the servo drives. Three movement exercises with increasing complexity were proposed: discrete motion, coordinated, and synchronized motion. Then, the success rate and time spent were analysed and compared in both situations. The experiment was designed so that the only difference between the two situations was the source of mechanical data information. Similar experiences, in which two groups (at least) are divided with a single differentiating element, can be found in the literature [31–33].

4.1 Experiment Resources

The surveyed students had two previous subjects in which PLCopen programming and motion control notions where studied. By the last year of the degree, they are already familiar with both the PLCopen standard and the motion libraries. However, obtaining the values of the mechanical parameters of the function blocks from the mechanical documentation has never been covered.

Fifty students in the last four months of their academic training participated in the experiment. The experiment was carried out in a classroom where each student had: a PC with a connection to the online form in which the answers were being collected, a calculator, a pencil and a ruler. A screen displayed a stopwatch in order to monitor the elapsed time of the test and provide a common time base. After the presentation and explanation of the experiment, based on the machine that can be seen in Fig. 8, the printed versions of mechanical and MMCS drawings were randomly and equally distributed (see Fig. A.1 and Fig. A.2 in the appendix A, respectively). The form and the timer were then activated, and the order was given to continue with the proposed exercises.

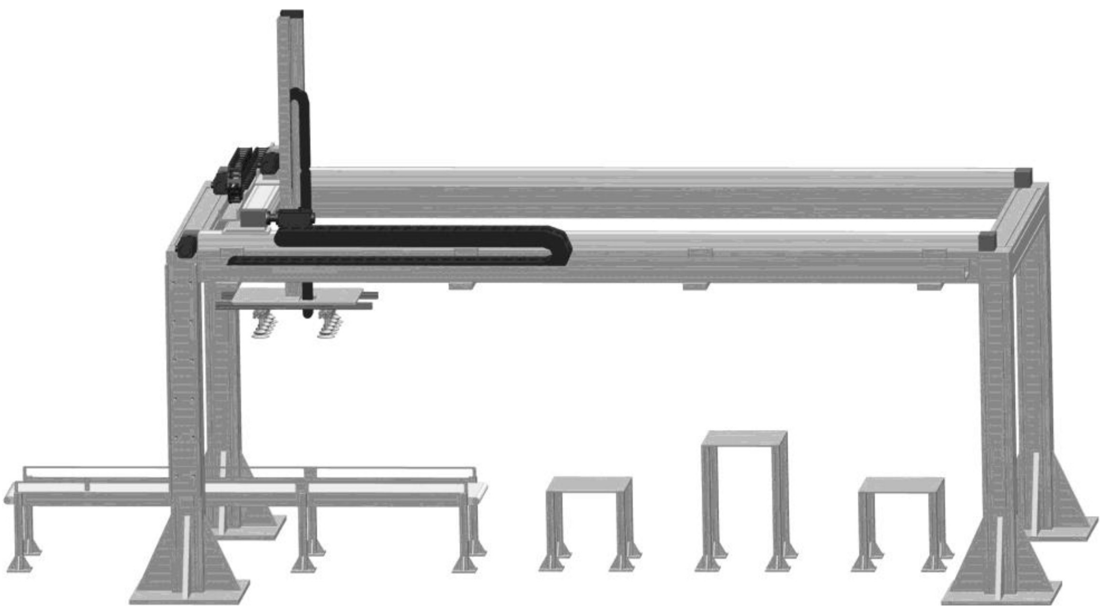

Fig. 8. 3D model representation of the machine of the experiment.

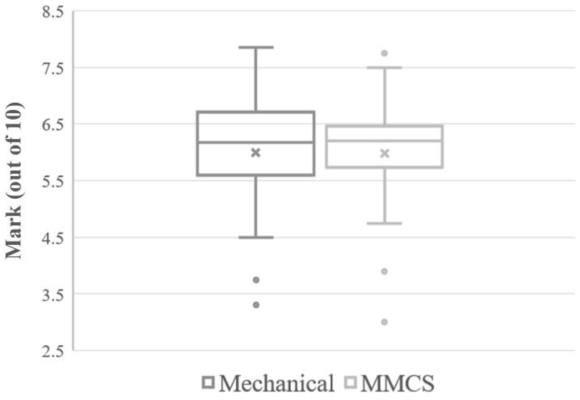

Fig. 9. Boxplot with the distribution of the average mark in programming subjects of student, according the MMCS group and the mechanical one.

Fig. 9 shows the boxplot with the distribution of the average mark in programming subjects of each student, according to the two groups in which students were divided after the distribution of the MMCS and the mechanical drawings. It can be seen that the average scores and the variances are very similar. Specifically, a mean of 5.74 and a variance of 2.48 for the MMCS group, and an average of 5.73 and a variance of 1.39 for the mechanical one. Therefore, the differences between using MMCS or not could not be associated with a bias in the students' previous knowledge.

4.2 Development

The experiment was divided into three parts. In the first, "Presentation and explanations": the authors of this article presented the context, objectives and development of the experiment to the students. The symbols and notation of MMCS, still unknown by the students until that moment, were explained. Next, the machine 3D view to perform the exercises and the three types of movements to be parameterized were also presented. This phase lasted 20 minutes. The second part, "Random distribution of mechanical and MMCS drawings" took about five minutes. Printed versions of the mechanical drawings and their equivalent MMCS ones were handed out alternately to the students, creating two groups. Next, access to the online questionnaire was activated and the test began. The third part was the exercise resolution. The duration of this phase was about 30 minutes. The anonymous online form consisted of eight steps, which are described below:

- Student profile: previous knowledge, marks in related subjects.
- Type of drawings used: mechanical or MMCS.
- Confirmation of stopwatch visibility.
- Order to start the test after having verified that all students are ready.
- Discrete movement exercises (timed phase). A statement with 3D drawing (see Fig. 10a and

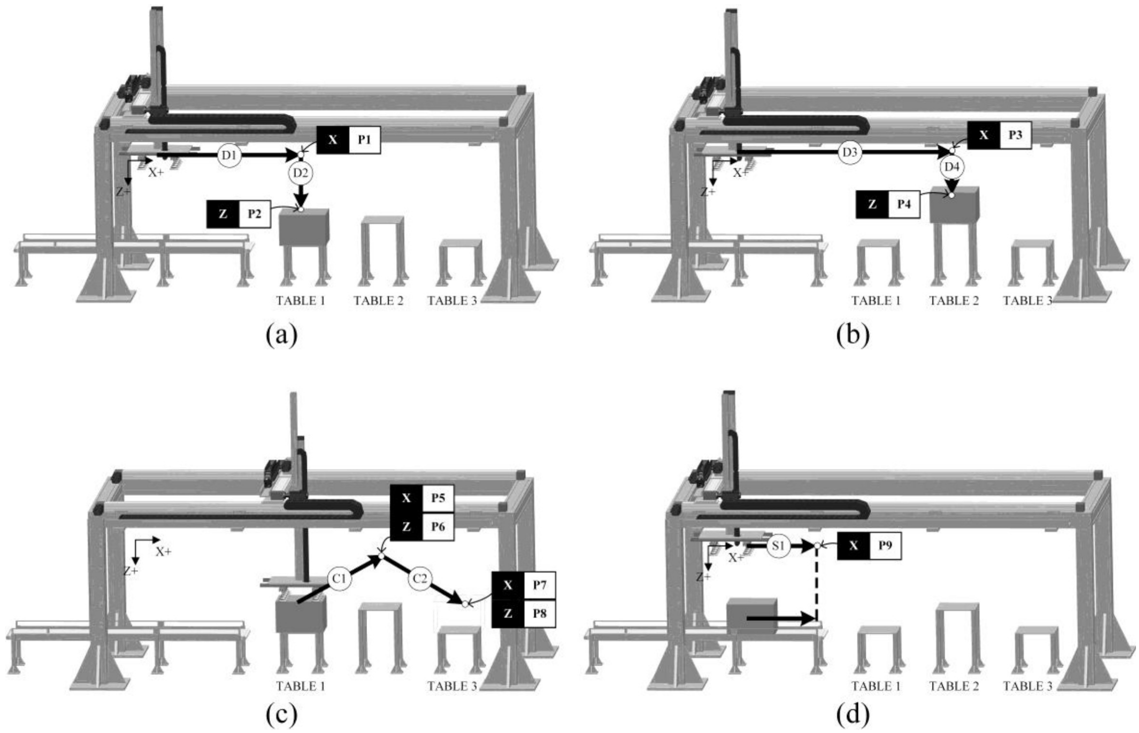

Fig. 10. 3D drawing of discrete, coordinate and synchronized movements exercise statement, respectively. (a) D1 and D2. (b) D3 and D4. (c) C1 and C2. (d) S1.

Table 1. Guide table of the movements of the test carried out

Figure	Motion	Servoaxis used	Mechanical value	Motion type	FB_Class	Parameter
10a	D1	X	P1	Discrete	MC_MoveAbsolute	Position
10a	D2	Z	P2	Discrete	MC_MoveAbsolute	Position
10b	D3	X	P3	Discrete	MC_MoveAbsolute	Position
10b	D4	Z	P4	Discrete	MC_MoveAbsolute	Position
10c	C1	X and Z	P5 and P6	Coordinated	MC_MoveLinear	Position
10c	C2	X and Z	P7 and P8	Coordinated	MC_MoveLinear	Position
10d	S1	X as slave	P9	Synchronized	MC_GearInPos	SlaveSync Position

Fig. 10b) and corresponding questions were shown to obtain the values of the position parameters of the four discrete MC_Move function blocks as answers. The objective was to move the TCP from a "rest position" up to the surface of the box located on "TABLE1" using two movements: "D1" and "D2". Then, other movements to "TABLE2" with "D3" and "D4", obtaining the points "P1" to "P4", as Fig. 10b shows.

- Coordinated movements exercises (timed phase). The objective was to move the TCP that would initially be holding the box up to "TABLE3" avoiding "TABLE2", carrying out movements "C1" and "C2". The students had to make sure that when passing over the centre of "TABLE2", the distance between the box and the table exceeded a certain value, obtaining the values of the coordinates "P5" to "P8" to parameterize two MC_MoveLinear function blocks (see Fig. 1). Fig. 10c shows the 3D drawing of the exercise.
- Synchronized movement exercise (timed phase). A statement with the 3D drawing (see Fig. 10d) and a question were shown to obtain the value of the parameter "SlaveSyncPosition" of the MC_GearInPos function block (see Fig. 1c) as an answer. The objective is to align the TCP "on the fly" over the center of the box without having to stop either the box or the servo drive (movement "S1"). For that, it is necessary to make use of a virtual axis that represents the movement of the box.
- General questions and comments..

Table 1 shows a summary of the movements and the values to be obtained along with their representation in Fig. 10 above. When the students filled in the answers on the form, they had to indicate the time that appeared on their stopwatch before continuing with the next exercise. In that way, the time spent in the resolution of each step can be calculated. The difficulty of the exercises is incremental, starting with discrete movements or PTP (point-to-point), followed by coordinated movements of two axes and ending with synchronized movements establishing a master-slave relationship. The main results of the experiment in terms of correct answers and spent times are presented below.

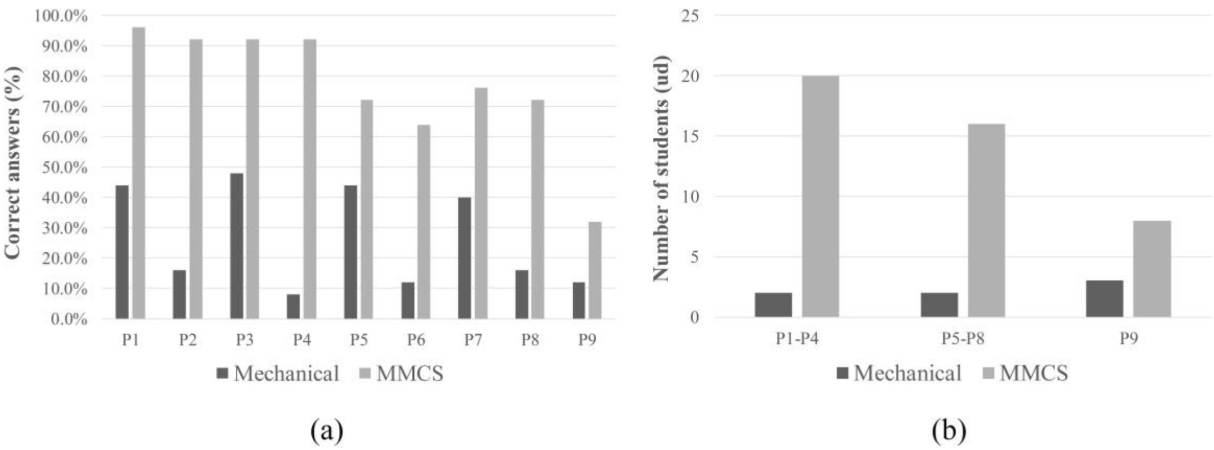

Fig. 11. Graphical results of the experiment (I). (a) Percentage of success by mechanical or MMCS drawings usage. (b) Distribution of the number of students who passed each complete exercise by mechanical or MMCS drawings.

5. Results

5.1 Correct Answers

Fig. 11a shows the percentage of correct answers for each of the parameters that the students had to calculate in both groups, MMCS and mechanical drawings. It can be seen that the hit rate among the students who used MMCS drawings is higher in all cases. It can also be observed that the hit rate decreases greatly within the group that used mechanical drawings when it came to calculating the coordinate values of the Z-axis. This may be explained because the zero point or origin of the Z-axis was defined in such a way that it coincides when the vertical axis is fully retracted and, thus, the position of the TCP is as high as possible with respect to the ground (symbol "Z+" of the TCP in Fig. A.2 in the appendix A). Therefore, as the TCP is lowered to the ground, the value of the Z-axis position increases. That detail was explained to the students before doing the exercises. The coordinate system of servo drives does not usually appear on mechanical drawings, but it is essential on MMCS ones.

The hit rate decreases in both groups as the exercise increases in complexity. It can be observed that, in both groups, the percentage of correct answers decreases significantly when calculating "P5" and "P6", values of "C1" (see Fig. 10c). Those values correspond to an intermediate point, through which the TCP has to pass to move the box and avoid hitting an intermediate obstacle, "TABLE2". The particularity of this point is that it does not correspond to any mechanical element. Points of this type are those that have to be calculated during the programming of the movements to define the path of the TCP.

In the third exercise, which is the most complex conceptually speaking, two different coordinate systems were used, one of the TCP itself and the other corresponding to the zero position of the virtual axis that represents the movement of the box on the conveyor belt. The hit rate is much lower than in the other exercises, but even so, the MMCS group practically triples that of the group who used mechanical drawings.

Another way to assess the correct answers is to consider that an exercise is valid only if all the parameters are correct because the machine will only work correctly in a real application if all the movements are correct. Otherwise, the malfunctioning could even cause collisions and accidents. Being strict and grouping the correct answers by exercise, the graph of correct answers is obtained in Fig. 11b.

Table 2. Statistical test for time spent for MMCS experimental group

Test	p-value	Result
Shapiro-Wilk normality	0.3398	Accept H0
Levene variance	0.2438	Accept H0
Welch T-test	2.624e-10	Discard H0, Accept H1

5.2 Time Spent

Fig. 12a shows the boxplot with the distribution of the exercise times for both groups. The data of the times spent are analysed with the Shapiro-Wilk normality test and a p-value of 0.3398 is given. The Levene variance test returned a p-value of 0.2438, accepting in both tests its corresponding H0 and giving the conditions to apply a T-test. Finally, a p-value is obtained in the Welch T-test of 2.624e-10, with 44.517 degrees of freedom, thus discarding H0 and accepting H1.

That is, a difference in the average time of performing the exercises is statistically confirmed for the group that used the MMCS. For the p-values, a statistical significance of 0.05 was considered. A summary is shown in Table 2. Fig. 12b shows the distributions of the times spent carrying out the exercises, taking into account the group they were in and whether the results were correct or not. In the case of the students who used MMCS drawings, similar average times are obtained, but in the case of the mechanical source usage, those who obtained correct results spent much more time.

5.3 Success Rate and Average Time

Fig. 13 shows the joint graphs of the percentage of success and the average time to obtain the values for both groups. It should be noted how the time for "P1" to "P4" decreases as the students become familiar with the mechanical documentation but increases again for "P5" and "P6", which are the intermediate points. For "P7" and "P8", the time goes down again since those are easier to obtain. The last point, "P9", increases the time required again. It is interesting to observe how the shape of the evolution of time is similar for both groups, but the group that uses MMCS drawings spent less time and with a higher hit rate.

6. Discussion

The experiment results validate the hypothesis that MMCS designs improve the understanding of advanced concepts of movements when compared with mechanical drawings and help to obtain essential mechanical information for the parameterization of the motion commands. Validation of the hypothesis is supported by the statistical significance of the results, since the group of students

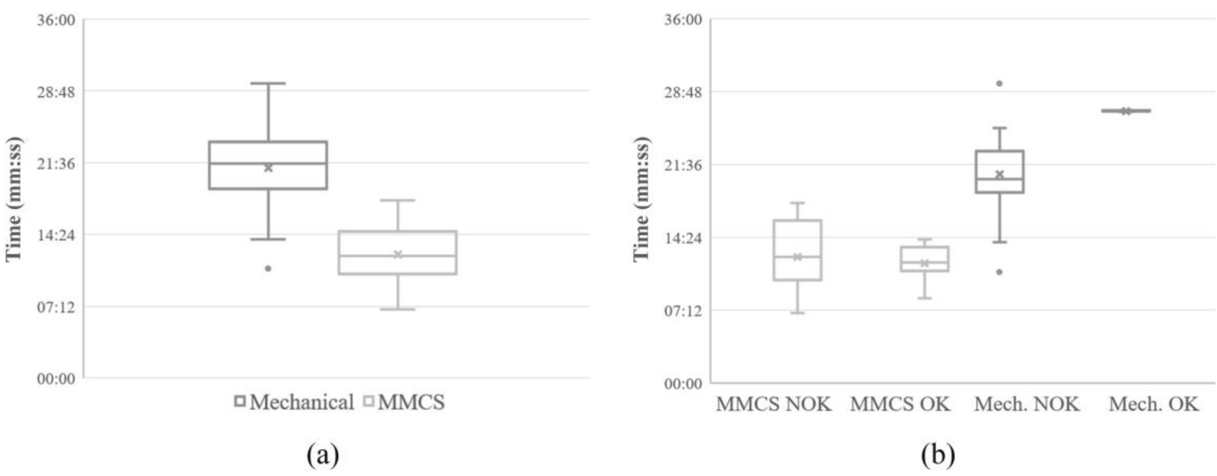

Fig. 12. Graphical results of the experiment (II). (a) Box plot of the total average time to complete the exercises depending on the use of mechanical or MMCS drawings and (b) depending on whether all of them were correct or not and the type of source used (mechanical or MMCS drawings).

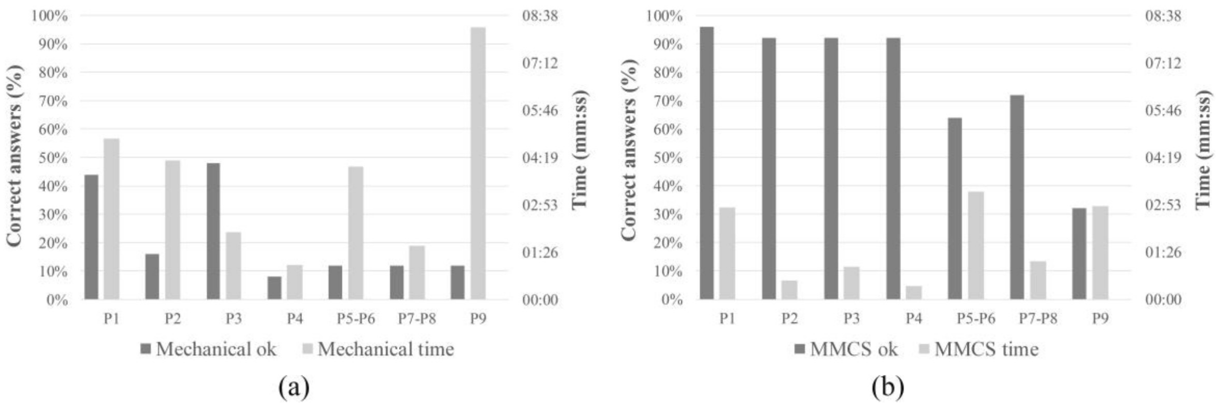

Fig. 13. Graphical results of the experiment (III). Percentage of success and average time spent per exercise by the use of (a) mechanical and (b) MMCS source.

with MMCS drawings obtained a higher hit rate in a shorter time, compared with the students who used mechanical ones.

The experiment highlights some of the new conventions suggested by MMCS. The proposed solution, for example, graphically identifies the ‘‘guided mobile element’’ and the ‘‘fixed guide element’’ in mechanics based on linear axes, and explicitly represents distances and limits that are relevant for the automation but not always represented in a mechanical graphical design. The experiment shows how automation students can identify faster and more accurately relevant machine physical information from a simplified mechanical document.

Furthermore, more complex concepts such as virtual or logical mechatronic concepts present in modern motion control automation programs are also introduced, including such things as virtual axes, new electronic events involving real and virtual axes, etc. The experiment shows that as the mechatronic concepts worked with become more complex (such as the virtual axes in the ‘‘Synchronized movement exercise’’ in Fig. 12d), the benefits obtained as a consequence become more obvious.

7. Conclusions and Future Work

A new systematic information representation system, ‘‘Mechanical and Motion Control Schematics’’ (MMCS) has been developed as an intermediate point between mechanical designers and automation designers.

The problem that MMCS aims to solve is how to reduce the communications issues that arise on the border between two technologies or between two areas of knowledge, particularly when one of them is undergoing a major advance (automation in this study). New concepts introduced into the more dynamic area of knowledge do not have an equivalent representation in the area that has undergone fewer changes (mechanical design in this study). Although the article focuses on the areas of mechanical design for machinery and its automation, the same strategy of enriching the design methods of the less evolved area with the new concepts emerging from the other could be used to reduce new communications problems between the disciplines.

To assess the contribution of MMCS to the teaching of motion programming subjects to students of a Bachelor Degree in industrial automation engineering, a comparative experiment was designed. This experiment has been restricted to the setting of an Industrial Automation Engineering Program in order to have a homogeneous experimental population consisting of students in the same subject area and with the same level of education. However, the method presented has been applied for several years in undergraduate teaching and has been well received by students. Moreover, this method is also beneficial for teaching, since it allows a sketch representation on the blackboard of machine elements in a systematic and simple way. Even though an MMCS blueprint is a simplified representation, similar MMCS blueprints are obtained for the same machine regardless of the designer or their background. This has not only facilitated student understanding, but it has also provided teaching staff with a tool for representing exercises more systematically, including new mechatronic concepts.

Future work will include repetition of the experiment with new users and extensions to the method that contemplate mechatronic configurations of increasing complexity. It would be necessary to consider extending this experience to other educational centres for greater validation. It might even be extended to the professional field since the problem is the same as the one detected in the educational field. A further step for this will be to evaluate the benefits of the methods in a Mechatronic master's degree, where students will come from different backgrounds (mechanical and automation) and have different professional experience and skills, etc. As a final remark, the use of MMCS becomes beneficial as an intermediate point to understanding mechanical drawings, without dismissing the use of the traditional detailed mechanical ones.

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Appendix

A. Drawings used in the experiment.

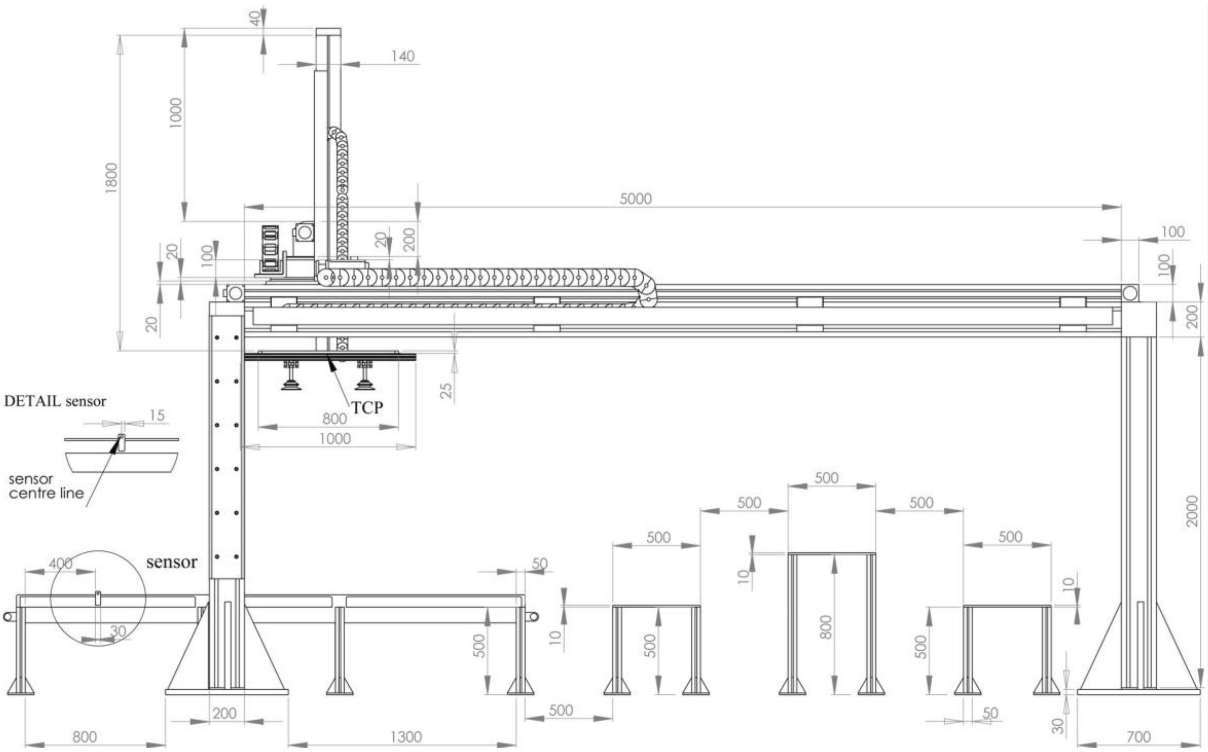

Fig. A.1. Mechanical drawing of the machine of the experiment.

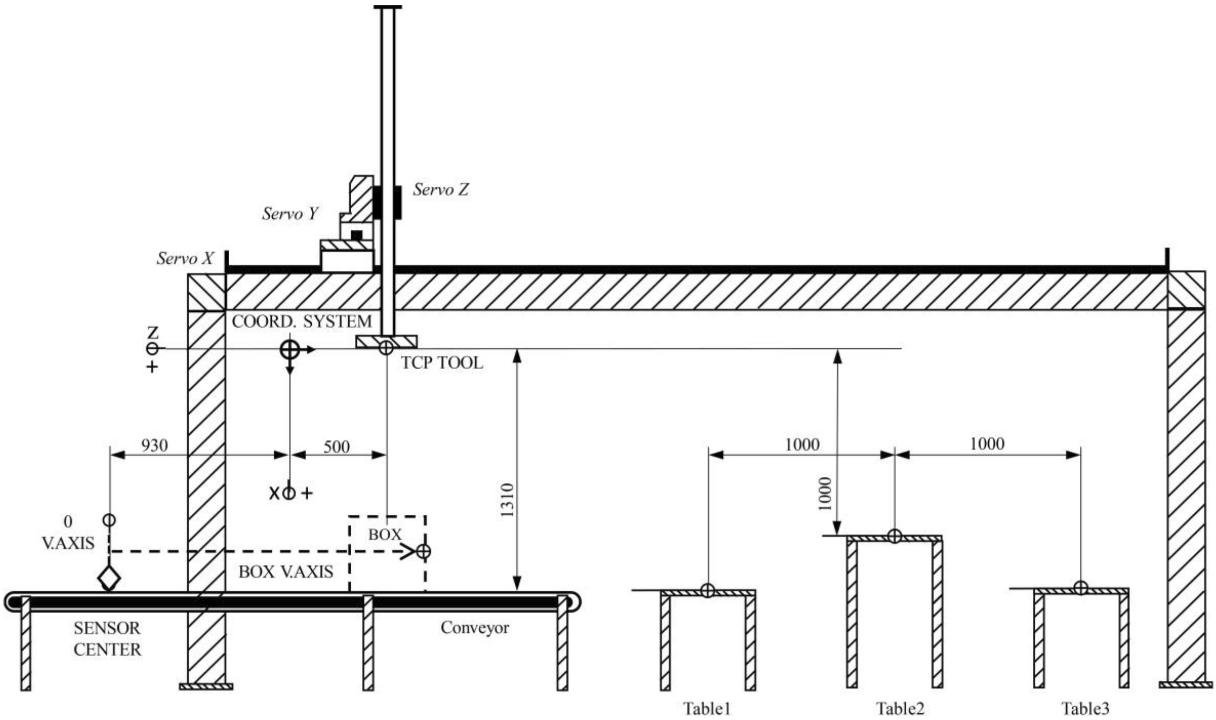

Fig. A.2. MMCS drawing of the machine of the experiment.

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