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Five Bar Parallel Plotter based on Construction Kits and Open Source Development Environment

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Abstract—**Five bar parallel kinematics are widely used for robots in industry, research and education. In this paper a five bar parallel plotter (FiBaPlot) is presented. With a plotting feature a simple accuracy check can be carried out. Hence the FiBaPlot is suitable for teaching and research issue. In this paper the development of a low cost FiBaPlot is described. The mechanical design is based only on construction kits. The plotter is controlled by a dual core ARM microcontroller. The electronic interface as well as the open source in the system (OSiS) with an integrated development environment (IDE) is presented. OSiS is based on the open source program Scilab/XCOS and is able to generate automatic code for rapid control prototyping. Finally, the use of FiBaPlot in a student project is presented.**

Keywords—five bar parallel kinematics, rapid control prototype, plotting

I. INTRODUCTION

Parallel kinematics are widely used for robots due to their high stiffness and good accuracy. A simple representation of parallel kinematics is given by a five bar parallel planar robot. This robot was considered in different research works to optimise the design [1], [4], [5], [8] and the control [2], [3], [6], [7]. In general, these works are related to robots for handling tasks. But also a five bar plotting robot was found [6]. In education the five bar parallel kinematics often is considered as a simple example to explain the forward and inverse kinematics as well as the dynamics in robotics. In the industry, they have not shown yet their complete potential for high speed palletization. However, the second author has already applied them on test tube filling with better results than the classic Cartesian solutions [10]. But even if this type of robot has been relatively studied, a five bar parallel plotter based on construction kits could not be found in literature. Due to the strict research nature of these projects, the control of these types of robots often were provided on a PC using a special software calculating the trajectories. This project has combined expertise in the areas of parallel robotics and micro-controllers. Rarely, the micro-controllers were implemented to control even simpler parallel robots or the outcomes were often mitigated by the performance limitations of the micro-controllers like Arduinos, [13]. The rationale behind this choice would be to prove that a parallel robot can be designed at cost rendering them accessible to small enterprises and even Universities. Inasmuch, an open source approach for the development of the control was not presented in literature up to now and will further materialize the affordability goal without any performance sacrifice.

II. CONSTRUCTION KITS

One of the main advantage of the five-bar parallel mechanism is that it can be dimensioned to avoid internal singularities, meaning those encountered within the workspace, [12]. One of the best well-known construction kits for mechanical prototyping is LEGO. Another mechanical construction kit is Meccano where the metallic parts and screws allowing improved prototyping with tighter fits. However, for the design of a five-bar parallel prototype to be displayed as an excellent proof-of-concept for parallel robots in industrial applications, a mechatronics design can commence by convincing engineering students. The simplest and still demanding application will be a plotter where stiff elements and adequate bearings are necessary. The robot performance includes relatively rapid displacements and sufficient precision to show sketches with smooth lines.
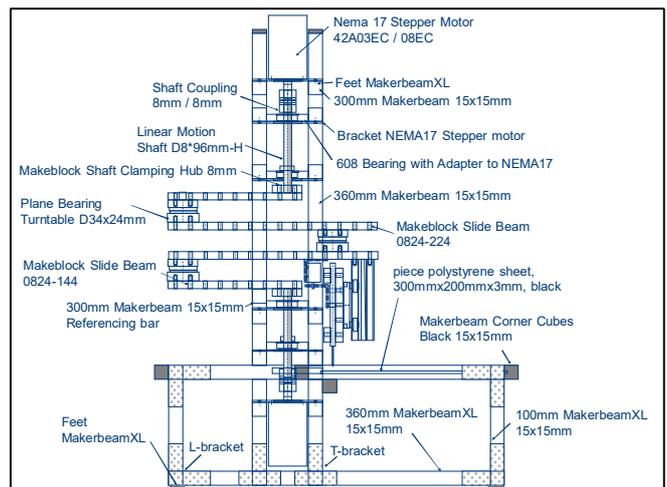

Fig. 1. Design concept using construction kits MakerBeam and makeblock

Rather than using single plastic components the construction elements should be made out of high quality metal and the selected components should be of industry-grade quality. And

for a lightweight, strong and affordable design, aluminium is selected. Especially for robot design, the construction kits called MakerBeam and makeblocks are preferred as it is possible to design the entire robot without mechanical manufacturing of additional components. The robot frame and the mounting of the drives are built using Makerbeam elements while the moving parts of the robot (arms, planar bearings and plotting device) are built by makeblocks elements (Fig. 1 and Fig. 2).

Hence, the robot could easily be built up by any education institution. The total costs of the plotter including electronics and control is less than 1.000 Euros.
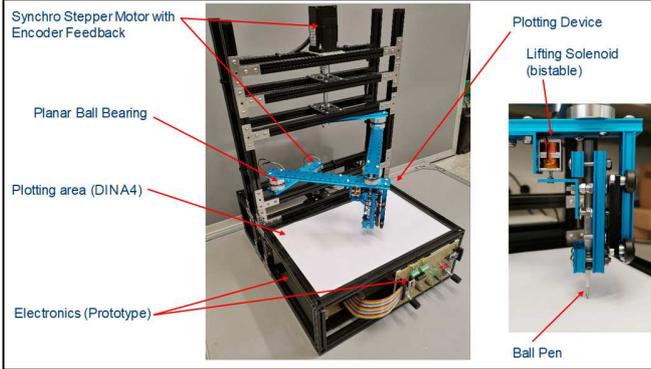

Fig. 2.   Dual Arm Parallel Scara Plotter

III. DIRECT AND INVERSE KINEMATICS

For the robot design analysis, its kinematics have to be calculated. The direct kinematics describe the relation between the angular position of the drives φ_1, φ_2 and the corresponding plotting point C, represented by a vector $\overline{C}$ in a fixed reference system O (Fig. 3). This means that the vector $\overline{C}$ is a function of the drive angle φ_1, φ_2 (1)

$$\overline{C} = f_d(\varphi_1, \varphi_2) \qquad (1)$$

The mathematical derivation of (1) is possible by different approaches [1], [4], [5], [6], [8]. Here we are using a simple vector based approach were vector $\overline{C}$ is given by the vectors to the points A, D and C (2)

$$\overline{C} = \begin{bmatrix} C_x \\ C_y \end{bmatrix} = \overline{A} + \overline{AD} + \overline{DC} \qquad (2)$$

We assume a symmetric design with the distance a and b for the bars and d for the distance of the driving points O_1 and O_2 (referring Fig. 3). Under these limits the single vectors can be calculated to:

$$\overline{A} = \begin{bmatrix} -\frac{d}{2} + a \sin \varphi_1 \\ 0 + a \cos \varphi_1 \end{bmatrix} \qquad (3)$$

$$\overline{AD} = \begin{bmatrix} AD_x \\ AD_y \end{bmatrix} = \frac{1}{2} \begin{bmatrix} d + a (\sin \varphi_2 - \sin \varphi_1) \\ a (\cos \varphi_2 - \cos\varphi_1) \end{bmatrix} \qquad (4)$$

$$\overline{DC} = \frac{d_{DC}}{d_{AD}} \begin{bmatrix} -AD_y \\ +AD_x \end{bmatrix} \qquad (5)$$

$$d_{AD} = \sqrt{AD_x^2 + AD_y^2} \qquad (6)$$

$$d_{DC} = \sqrt{b^2 - d_{AD}^2} \qquad (7)$$

where d_{AD} represents the length of vector $\overline{AD}$ and d_{DC} represents the length of vector $\overline{DC}$.
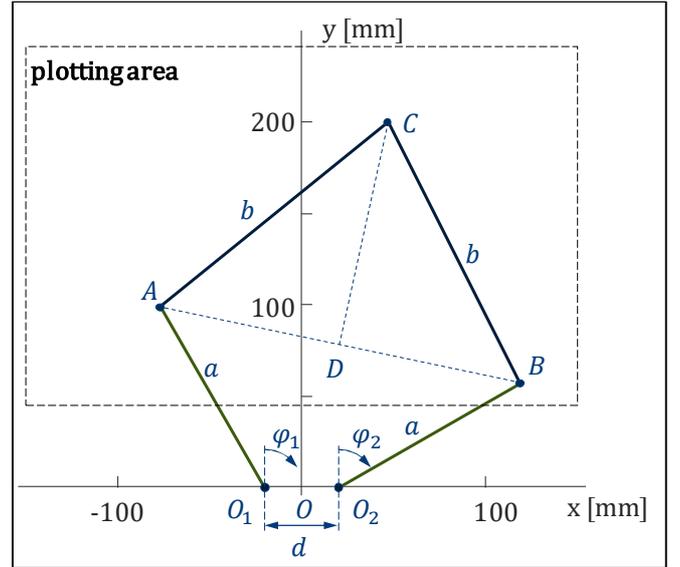
Fig. 3.   Calculation of direct kinematics

By using the direct kinematics, the workspace of the plotter can be analysed. The basic specification for the design was a plotting workspace of 200x300mm (DIN A4). With the limitations given by the elements of the construction kit and the stepping motor an optimal design was found. Therefore, we use full factorial design to optimise the plotting area. Fig. 4 shows the plotting area as well as all possible plotting points for a typical stepper drive with 1.8° stepping angle.

Fig. 4.   Plotting limits with stepping resolution of 1.8°

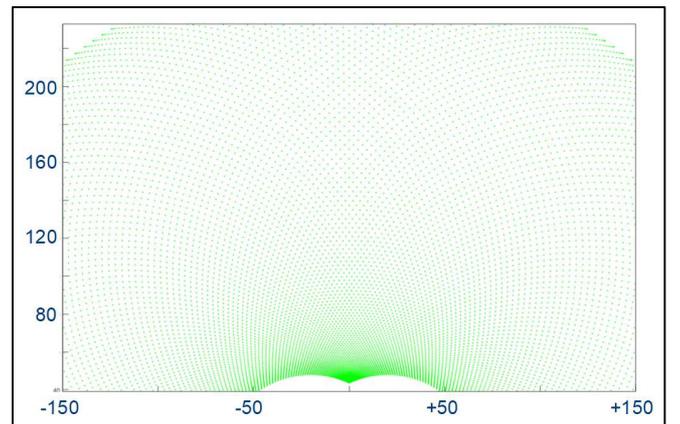The robot resolution is appearing in the discretized plot. The outcome shows that it is depending on the actual plot position. The highest resolution can be found in the middle at the bottom meaning the area the closest to the arm fixed joints while the lowest resolution is given in the upper left and right corner of the plotting area meaning at the extended arm positions. In areas with lower resolution, initial experiments with the 1.8° step angle of the joint motor, show that the outcome will not be sufficient for a good plotting result. Thus, a motor driver with micro stepping has to be used.

To control the robot, a trajectory in the x-y frame will be the set value to follow. These set values have to be transferred to the set vales for the drive angle φ_1, φ_2. This relation is given by the inverse kinematics (8).

$$(\varphi_1, \varphi_2) = f_i(C_x, C_y) \tag{8}$$

The drive angle is calculated by (9) and (10) from the legs to the corresponding vector $\overline{O_1 A}$ and $\overline{O_2 B}$ (see Fig. 5).

$$\varphi_1 = atan2 \frac{O_1 A_x}{O_1 A_y} \tag{9}$$

$$\varphi_2 = atan2 \frac{O_2 B_x}{O_2 B_y} \tag{10}$$

These vectors are given by the sum of the vector $\overline{O_1 D_1}$, $\overline{D_1 A}$ (11) and $\overline{O_2 D_2}$, $\overline{D_2 B}$ (12) where D_1 and D_2 are the height base point of the triangle $O_1 A C$ and $O_2 B C$ (11), (12).

$$\overline{O_1 A} = \overline{O_1 D_1} + \overline{D_1 A} \tag{11}$$

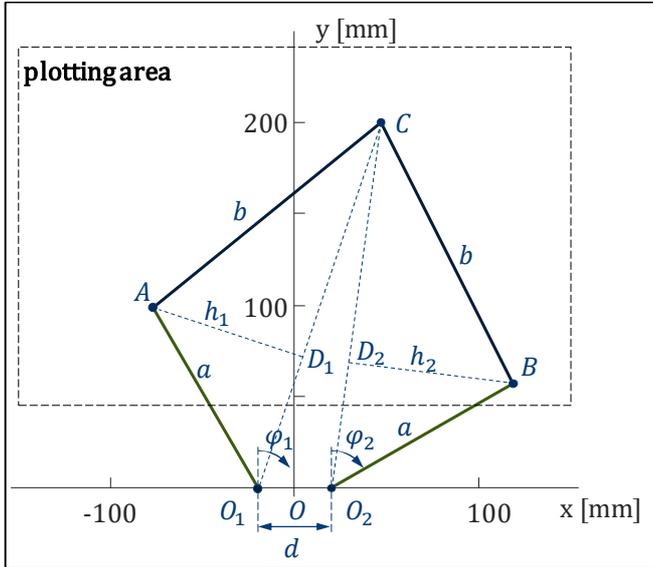$$\overline{O_2 B} = \overline{O_2 D_2} + \overline{D_2 B} \tag{12}$$

Fig. 5.   Calculation of inverse kinematics

The vectors to the height base point are calculated by the relation of the length $d_{O_1 D_1}$ in relation to $d_{O_1 C}$ of the vectors

$\overline{O_1 D_1}$ and $\overline{O_1 C}$ as well as the length $d_{O_2 D_2}$ to $d_{O_2 C}$ of the vectors $\overline{O_2 D_2}$ and $\overline{O_2 C}$ (13), (14).

$$\overline{O_1 D_1} = \frac{d_{O_1 D_1}}{d_{O_1 C}} \begin{bmatrix} C_x + \frac{d}{2} \\ C_y \end{bmatrix} \tag{13}$$

$$\overline{O_2 D_2} = \frac{d_{O_2 D_2}}{d_{O_2 C}} \begin{bmatrix} C_x - \frac{d}{2} \\ C_y \end{bmatrix} \tag{14}$$

The lengths to the point C can easily be calculated by the vectors elements (15), (16). The length to the height base point is given by the set of cathets in a general triangle (17), (18).

$$d_{O_1 C} = \sqrt{\left(C_x + \frac{d}{2}\right)^2 + C_y{}^2} \tag{15}$$

$$d_{O_2 C} = \sqrt{\left(C_x - \frac{d}{2}\right)^2 + C_y{}^2} \tag{16}$$

$$d_{O_1 D_1} = \frac{a^2 - b^2 + d_{O_1 C}{}^2}{2 d_{O_1 C}} \tag{17}$$

$$d_{O_2 D_2} = \frac{a^2 - b^2 + d_{O_2 C}{}^2}{2 d_{O_2 C}} \tag{18}$$

Finally, the vectors $\overline{D_1 A}$ and $\overline{D_2 B}$ are at right angle to the corresponding vector to the point C and the length of these vectors is the relation of the heights h_1 and h_2 of the triangle in relation to the length $d_{O_1 C}$ and $d_{O_2 C}$ of the vector $\overline{O_1 C}$ and $\overline{O_2 C}$ (19), (20). The heights are given by the set of Pythagoras (21), (22).

$$\overline{D_1 A} = \frac{h_1}{d_{O_1 C}} \begin{bmatrix} -C_y \\ C_x + \frac{d}{2} \end{bmatrix} \tag{19}$$

$$\overline{D_2 B} = \frac{h_2}{d_{O_2 C}} \begin{bmatrix} C_y \\ -C_x + \frac{d}{2} \end{bmatrix} \tag{20}$$

$$h_1 = \sqrt{a^2 - d_{O_1 D_1}{}^2} \tag{21}$$

$$h_2 = \sqrt{a^2 - d_{O_2 D}{}^2} \tag{22}$$

The result of equation (9) and (10) will offer multiple solutions as the position C can be given by different sets of drive angle φ_1, φ_2 (see Fig. 6).

Constraints are necessary to avoid the ambiguity for the inverse kinematics. For the plotting area a simple angle constraint can be found (23):

$$0 \leq \varphi_A \leq \pi \ \ and \ \ \pi \geq \varphi_B \geq 2\pi \tag{23}$$

To avoid additional trigonometric calculation, the angle constraint is replaced by a vector constraint. If the angle constraint is valid the vector $\overline{O_1C}$ and $\overline{O_2C}$ can be calculated according to (24) and (25).
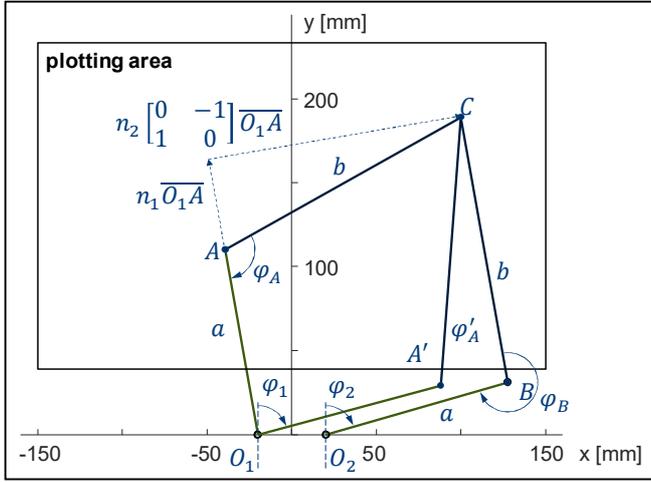

Fig. 6.   Calculation of inverse kinematics

$$n_1 \begin{bmatrix} O_1A_x \\ O_1A_y \end{bmatrix} + n_2 \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} O_1A_x \\ O_1A_y \end{bmatrix} = \begin{bmatrix} O_1C_x \\ O_1C_y \end{bmatrix} \qquad (24)$$

$$m_1 \begin{bmatrix} O_2B_x \\ O_2B_y \end{bmatrix} + m_2 \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} O_2B_x \\ O_2B_y \end{bmatrix} = \begin{bmatrix} O_2C_x \\ O_2C_y \end{bmatrix} \qquad (25)$$

with gain $n_2 \geq 0$ and $m_2 \geq 0$. After processing the x and y equations and replacing gain n_1 and m_1 the constraint will be given by (26) and (27).

$$O_1A_y \cdot O_1C_x \geq O_1A_x \cdot O_1C_y \qquad (26)$$

$$O_2B_x \cdot O_2C_y \geq O_2B_y \cdot O_2C_x \qquad (27)$$

IV.   ELECTRONICS FOR CONTROL

For plotting a line in the x-y frame the inverse kinematic has to be calculated to get the set values for the drive angle φ_1, φ_2. A controller for these set values will be a multivariable control with linearization using the inverse dynamics [2], [7]. Sufficient computation power is necessary for the real time calculation of the control law.

In literature a PC is proposed to compute the control algorithm [2]. However, the normal computers are not considered proper for real-time operations and relatively unreliable in the industry. The trend is to move forward with implementation of micro-controllers which have recently shown their potential in serial robotics. [ref] However, the simpler micro-controller provides for restricted memory, programming and computational capacity which may hinder the necessary two-level controls.

In this work, we present a low cost dual core microcontroller STM32H745 instead of using a PC (Fig. 7) which offer all the computer advantages including access to all languages such as Python and C. The two core system is well suited for the two-

layer control strategy. One core (CM4) is calculating the lower control layer with current actuator joint servo or feedback control of the stepper motors. The other core (CM7) is handling the upper control layer processing the trajectory control which is required for changing from the end-effector task space to the actuated joint space including inverse kinematics and dynamics for trajectory pursuit. The robotics control difficulties lies in its multivariable control nature.
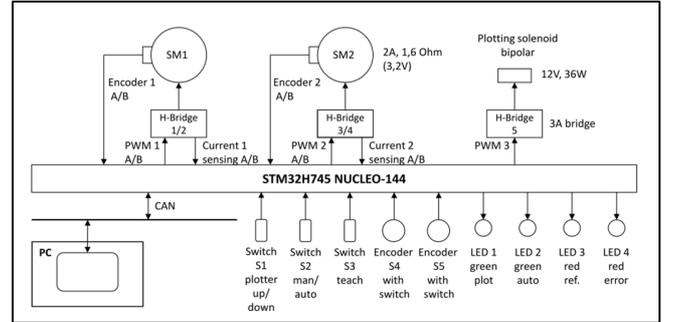

Fig. 7.   Control of Plotter based on a dual core microcontroller

For motor drive and current sensing integrated circuits are used (TABLE I.). The drive angle is measured by incremental encoders with 4000 increments per turn. A CAN bus interface is integrated so that set values can be transferred by external devices. For parameter setup and update of the program, a personal computer is also available using USB connection. The plotter can also be operated in standalone mode using a simple HMI with LEDs and switches.

TABLE I.   ELECTRONIC COMPONENTS

Electronic components	
Description	**Type**
Microcontroller	STM32H745
Motor Driver	DRV8871
Current Sensing	ACS732
Encoder Amplifier	AM26LS
CAN Transceiver	SN65HVD230

V.   INTEGRATED DEVELOPMENT ENVIRONMENT

For the development of complex control algorithm, rapid control prototyping systems are used to reduce development time and possible errors. In general, the Matlab/Simulink simulation standard is provided with a real time hardware extension from e.g. XPC, dSpace or Quanser. But these development environments are very expensive, often making classic robotics out of reach for even small enterprises. To achieve the affordability goal, we implement an open source environment based on Scilab/XCOS. XCOS provide all necessary functions comparable to Simulink which means that the development of an algorithm is block diagram oriented (Fig. 8). Special blocks were developed to cover the hardware: motor driver with current measurement, angle measurement, plot on/off and a ready block to indicate a correct start up with encoder initialisation. Scilab and XCOS offer an automatic code generation but for version 6.0.2 some bug fixes were necessary.

In addition to the bug fixes, the hardware blocks were implemented to the automatic code generation.

Special interface blocks are developed for variable input and output. These microcontroller variables can be accessed by OSiS-IDE running on the PC.
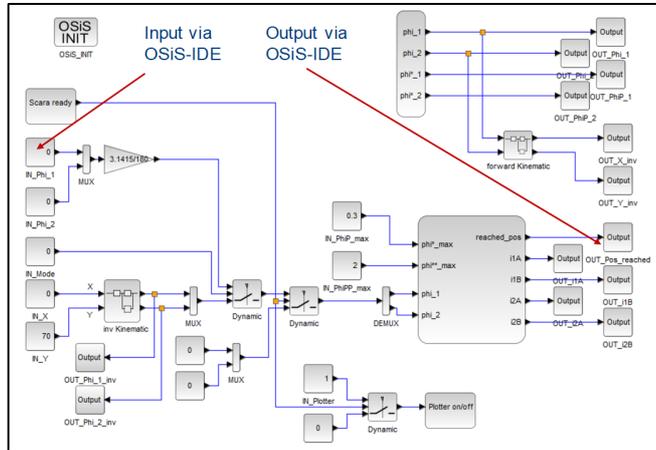

Fig. 8. Example of control algorithm in XCOS

After the algorithm configuration, a generation and upload of the program to the microcontroller is carried out by the OSiS-IDE (Fig. 9).
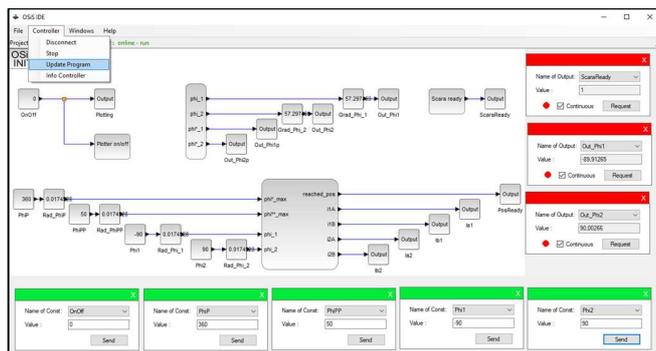

Fig. 9. OSiS-IDE for Program Update, Setup and Measurement

OSiS-IDE uses standard open source GNU C-compiler and linker to generate the program. The upload is done by a special USB-bootloader program that was also developed in this research work. This approach avoids compiler or linker error so no debugging interface to the microcontroller is necessary.

The input and output blocks can be assigned special labels in XCOS. These labels are the link to the input and output window in OSiS-IDE. To indicate input variables in OSiS-IDE a green bar can be seen at the top of the window while the output variable shows a red bar. The transfer of variable is done after pressing the button "send" or "request" while the request can be repeated continuously.

VI. Plotting Results

Examination of plotting is not as banal as it may seem in the first instance, as signal precision can visualise by line smoothness and continuity.

The robot setup together with the development environment Scilab/XCOS and OSiS-IDE is used by undergraduate students of the Bachelor course Mechanical Engineering with a specialisation in Mechatronics. The objective for the student is to build up the inverse kinematic model in Scilab/XCOS and to draw specific typical geometric shapes (square, triangle, circle). At the beginning the students will simulate the plotting process. After successful simulation the algorithm will be implemented in the robot setup to analyse the plotting results on a real hardware environment. In general, the students will recognise a difference between ideal simulation result and real life situation (Fig. 10). As a first approach the students are using only the inverse kinematics to generate set values for the angle control of the drives.
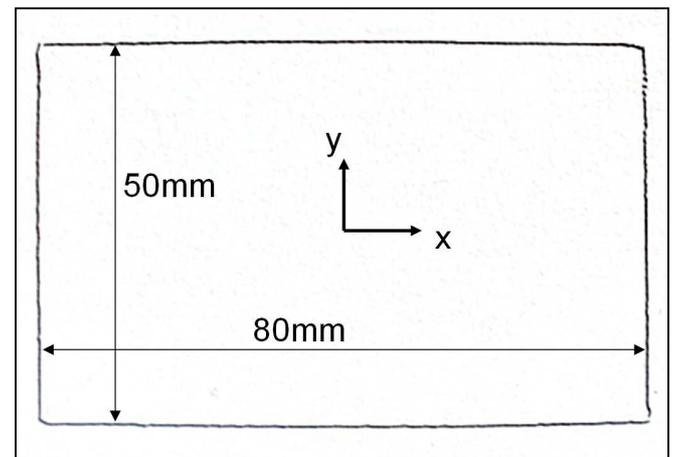

Fig. 10. Plotting Result with uncertain parameters [9]

These difference are the origin for a deeper analysis of the system done by the students. The analysis includes uncertain parameters of the setup, friction and also the control algorithm of the setup. With the background of a mechanical engineering education the students are able to consider the kinematic but also the dynamic model for the control law to improve the accuracy of the plot.

VII. Conclusion

In this paper, the design and construction of a five bar parallel manipulator is presented to achieve the plotter tasks. The plotting results should a consistent outcome with smoothness allowing to appreciate good precision.

The kinematics and inverse kinematics are given by a set of vector geometry. This allowed to examine the workspace and its resolution related to the selected stepper motor resolution.

It could be shown that the construction could be based only on industrial grade construction kits. For this design a combination of the construction kits MakerBeam and makeblocks were used.

In general, the control of this kind of robot prototype is done on a powerful PC which does not correspond to an industrial application. Here, we have shown that modern microcontroller with dual core processors, based on ARM technology are able to replace PC based control or traditional dedicated robotic controllers. Hence, a low cost solution for the double layer

trajectory control is possible. And we demonstrate a low costs development environment based on Siclab/XCOS for rapid control prototyping. The robot is basically used in education for student projects but shows potential for extrapolation to industrial processes confirming prior work. A plotting result of a student project is presented. Further work has to be done to implement different multivariable controls in the future.

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● **The below form will not be published, but it is necessary to help with the review process.**

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