Virtual prototyping, physical structure development and PC control of a double arm (five link) SCARA robot

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Abstract. The research presented in this paper is linked to parallel kinematics robots, their performances evaluation and analysis of their integration opportunity at industrial level. Along this research a double arm SCARA robot (including planar parallel kinematics of a 5 links / 2 DOF mechanism) was developed. The first stage of the project consisted of robot physical structure 3D modelling. The second stage of the project was oriented towards kinematic modelling of robot's mechanism. Next, in the third stage of the project the real robot was built, including the mechanical structure, the sensorial and electrical driving system for the planar mechanism, the pneumatic driving system for the vertical axis and the vacuum gripper. The fourth stage of the project consisted of configuring the robot controller so that it could be programmed and controlled through a PC. This implied the establishment of communication protocols between the robot's PLC and the PC, the development of the programming & control software interface for PC robot control. Using this interface, the robot was programmed to perform a pick-and-place application. In the final stage of the project the repeatability of the robot was measured in order to evaluate the accuracy characteristics of robot's parallel kinematic structure.

1. Introduction
Presently, one of the most dynamic domains for industrial robots implementing is the electronics industry, specific new robotic applications for different related fields activities being developed every day. Micro-electronic components manufacturing and electronics product's assembling, represents the most important segments in electronics processes automation, targeting mainly robotic tasks accuracy and productivity improvement. Although at this moment most industrial applications usually integrate serial joint robot structure (articulated arm, Cartesian or SCARA robots), the parallel kinematics robot architectures have several inherent advantages in terms of increased speed and accuracy [1]. From this point of view, the most used parallel kinematics robot architecture in electronics industry is the delta robot, (only few models of hexapod robots being used). However, for these fields of activity another type of parallel robot structure has been developed for some specific tasks: the double arm SCARA robots (including planar parallel kinematics of a 5 links /2 DOF mechanism). Accordingly, the vertical translational axis stroke, this robot architecture may have two basic versions: the "short" and the "long vertical axis stroke" versions. First version of IRs (short vertical strokes) is high-performance systems especially used for micro-handling, being unbeatable in precision, speed and compactness [2]. These robot units with 4 DOF are very compact and ideal for micro assembling mobile phones, watches, or hearing aids and other micro-electronic components assembly. The second robot version (long vertical
stroke) units with 3 or 4 DOF include a large range of robot models for wafer handling operations, their implementation being a standard for both atmospheric and vacuum wafer's manipulation, transport, inspection as well as micro-electronic components (vacuum) manufacturing processes. The research presented in this paper is directly referring to first version of IRs (short vertical strokes) as part of a study focused on parallel kinematics robots architectures development, their performances evaluation and analysis of their integration opportunity at industrial level.

The research presented in this paper had five objectives: conceptual constructive and functional synthesis of the robot, 3D parameterized synthesis, the practical realization, programming and direct command via a PC of a SCARA robot with a closed cinematic chain structure [3].

2. Current state of the research
After a thorough study [3] and a comparative analysis of several constructive robot variants with SCARA architecture, the DexTAR Ver 1 didactic robot was considered to be a reference model [4] (see figure 1).

In the realization of this didactic robot, a vacuum end-effector was used which is driven in the Z direction by a linear pneumatic motor, having a fixed stroke of 10 mm, and for the actuation of the arms, they used hollow shaft motors.

The general robot assembly (including all facilities specific to the mechanical drive and control) made in the final form and described by the authors under this article is completely assembled both mechanically and electrically (see figure 2). It was programmed to reach 8 fixed data points in the program, and the robot's program was done both to demonstrate the points it can reach and to demonstrate how it works.

Figure 1. DexTAR Ver 1 didactic robot: a. Real model; b. Virtual prototype: 1 - the base plate on which actuators are mounted; 2 - the first set of arms; 3 - the second set of arms; 4 - end effector; 5 - drive actuators.

Figure 2. The current state of the research - The general robot assembly completely assembled both mechanically and electrically.

The following elements have been acquired for the robot's physical realization:
- Mechanical: toothed belt sprocket T5; tooth belts T5 x 400; Bearing; lock bolts; Bosch Rexroth sections; corner profiles; multiple 6000 series aluminum semi-finished products; pneumatic cylinder FESTO; SMC solenoid valve; SMC pressure regulator ; SMC pneumatic hose; SMC pneumatic couplings; support plate.
3. Conceptual constructive and functional synthesis of the robot

The LINKAGE simulation program was used to configure and model the robot mechanism. The elements of the mechanism were assembled and tested to check the robot's mobility. With the LINKAGE package, the positions of the arms were determined for both the robot's extreme points, as well as for positions where the robot's arms do not have to reach (see figure 3, figure 4).

The geometric modelling of the robot has been performed for different sets of values of its constructive-functional parameters and the work space boundaries that can be achieved with each set of such parameters have been evaluated.

Finally, according to the definition of operating limits of the real robot model, dimensions have been set for the elements of the robot's mechanical structure: arm 1 = arm 2 = arm 3 = 200mm, and the distance between the rotation axes = 170mm (see figure 5).

Figure 3. LINKAGE simulation program - Simulation of arm movement.

Figure 4. LINKAGE simulation program - highlighting points of singularity.
Figure 5. Overall dimensions of the robot and upper view: 1 – base links; 2 – child link; 3 – child link.

The mechanism modelling using the LINKAGE software is essential for both trajectory planning and for integration with a future PC-based interface for command and programming, taking into account the fact that developing geometric and kinematic models of the mechanism will be required. In order to achieve this goal, it is very important to analyze the kinematic behaviour of the mechanism and to identify the singularity situations. Therefore, by using the LINKAGE software, four singularity configurations were identified, all being based on the alignment of the 2 and 3 segments (as identified in figure 5). Two of these singularity configurations are illustrated as examples in figure 4. For trajectory planning, these configurations should be avoided both as target points and also as passing points during trajectory generation.

The structure of the robot arms is illustrated in figure 5 by assigning numbers to the segments. The parallel structure of the five-bar robot comprises of two articulated arms that meet at the end-effector level. Each arm includes a base link (numbered as 1 on both arms) and a child link (numbered as 2 on the left arm and 3 on the right arm). The positioning in the planar cartesian workspace of the end-effector is generated by composing the movement of both axes accordingly, due to the parallel nature of robot kinematics.

4. Major steps in the realization of the experimental prototype of the robot

In this paragraph the major stages that led to the realization of the experimental prototype of the robot are synthesized. These are:

- 3D design of the robot virtual prototype;
- Manufacturing the mechanical components based on the execution drawings;
- Assembling the robot mechanical part;
- Assembling pneumatic components;
- Assembling electrical components.

For the 3D design of the robot's virtual prototype, the CATIA V5 R21 computer assisted design software was used. All component parts were made separately in the Part Design module and assembled using the Assembly Design module. Due to the CAD bases made available to the users by manufacturers, some components have just been assembled.
Pinions have been chosen to achieve a 1:4 reduction ratio between the engine spindle and the drive shaft of the arms. This helps for a higher torque on the drive shaft of the arms, which leads to higher accelerations in fast moving movements. At the same time, the reduction ratio also improves the positioning accuracy of the robot. For high mobility, the compressed air circuit for end-effector action was designed through the inside of the arms, bolts and drive shafts in order to allow the free rotation of the arms. To lift the support plate and the whole assembly, Bosch Rexroth 40x40 profiles were used. These profiles offer a high rigidity and easy assembly due to the corner joints and dedicated fixing elements. After finishing the 3D parts, they were assembled together resulting the final form of the virtual prototype which is shown in figure 6.

Figure 6. Final assembly of the robot – virtual prototype.

The next step was the manufacturing of the mechanical components (see figure 7 and figure 8) based on the execution drawings made in CATIA V5 R21. Since the robot arms were first designed – being the main structural elements, component construction began with the execution of the arms.

For the support of the motors (dimensions 60x60x40), and for the robot arms (dimensions 30x30x205) a 6000 series aluminium alloy has been selected - to be as light and resilient as possible. Likewise, for all robot axes and bolts, stainless steel category 304 material was used.

The joint between the two segments includes a pack of 2 radial ball bearings in order to support radial loads and reduce friction. The bearings were encased in the main body of the mechanism links.

All machining was done on CNC machine tools, and all the parts were checked after machining to fit the specified tolerances. The quality control was focused towards functional surfaces.

After executing all necessary components, the robot was assembled. The mechanical structure of the final assembly of the robot is presented in figure 9.

Figure 7. Machining: a. roughing; b. motor pinion pocket; c. roughening arms; d. shaft machining.
Then, next stage consisted of assembling the pneumatic components (see figure 10) which included quick hose couplings, solenoid valve, pressure regulator, pneumatic cylinder of the end-effector and hoses. After the assembly of the mechanical part and the pneumatic part of the robot was complete, the electrical components for the industrial environment were mounted, including encoders, sensors for confirming the "0" position of each arm, the emergency stop button, the connection box, the electric panel, etc. (see figure 11). In order to have a precise control of the robot movements, OMRON incremental encoders with 1600 pulses per rotation were used. The integration of the OMRON incremental encoders allowed the configuration of a closed loop control as a servo drive system. The measurement is made indirectly at the drive shaft. The drivers of the motors were set up on a microsteps configuration with 1600 pulses per revolution. All components of both the robot's electrical board and external components have been labelled for rapid identification according to the electrical and / or pneumatic scheme.

In order to control the robot and to provide a complete system capable to be programmed and integrated in an industrial environment, a Panasonic FP-X0 L40MR PLC was used. The specifications of the PLC are illustrated in table 1.

| Parameter       | Value                               |
|-----------------|-------------------------------------|
| Input / output  | 24 V DC input, 24 points            |
|                 | 0.5 A/5 - 24 V DC transistor output, 4 points |
|                 | 2 A relay output, 12 points         |
| Program         | 8 k steps                           |
The pneumatic scheme was made using the FESTO FluidSim software. The pneumatic circuit included an air tank for storing a larger volume of air at a pressure of about 6 bar, a pressure regulator that must be set to a maximum of 1 bar, a pressure gauge to control the pressure, a 3/2 electrically controlled distributor, a pneumatic cylinder with simple action.

Figure 10. Assembling pneumatic components: (a) pressure regulator; (b) pneumatic electrovalve; (c) pneumatic cylinder for the end-effector.

Figure 11. Assembly of electrical components: (a) robot electrical panel; (b) connections box; (c) PLC.

5. Robot programming
The robot programming was done in Panasonic's software for the Panasonic programmable machine - FPWIN GR V2.91 (figure 12) programming mode chosen being ladder. The robot can work independently on the program loaded in the programmable machine, but it can also be controlled directly from the computer via the programmable programming interface.

The first step in the robot programming was to choose the type of programmable controller - FP-X0 L40R. The next step was to set up the programmable machine and then the Y0, Y1 / Y2, Y3 output configurations as dedicated frequency pulse outputs. Motion control is made in servo mode. The programmable machine has been configured to verify that the number of pulses sent to the drivers is identical to the number of pulses received as a response from encoders. This is possible thanks to the 1600 pulse per rotation of the motor shaft driver setting and high-resolution encoders. After completing all configurations, follow proper programming.

Because the encoders used are incremental and not absolute, when feeding the robot with electricity,
It is necessary to perform the "0" procedure (see figure 12). Before performing the calibration procedure and during this step, the robot can not enter in the automatic mode. During calibration, the yellow bulb blinks, indicating that the calibration procedure is in progress. At the end of the calibration, the yellow light goes off and the red light comes on, this indicates that the robot is in STOP mode and waits until the green button is pressed to enter automatic mode (see figure 12). To control the movement of the robot in an independent mode, a number of points in which the robot has to reach, with different speeds and accelerations, has been loaded into the programmable memory (see figure 14).

Figure 12. FPWIN GR V2.91 SOFTWARE - section of the robot programming.

Figure 13. The calibration procedure.

Figure 14. Configure the first movement of the robot.
6. Conclusions
After virtual prototyping, physical structure development and PC control of a double arm (five link) SCARA robot with closed cinematic chain structure, it has been tested to measure repeatability accuracy. As a result of the measurements, the accuracy was below 0.01 mm.

Another conclusion is that no hollow shaft motors similar to those used in the DexTAR Ver 1 didactic robot have been used, and the drive system has been modified - a 1:4 reduction ratio has been added between the engine spindle and the drive shaft, which has improved the accuracy and the necessary torque to be developed by the motors has been reduced.

During the configuration of the kinematic model of the robot, it was concluded that one of the main issues of developing an experimental / didactic model of a robot based on a five-bar mechanism is linked to the high number of singularity configurations and the relatively complicated direct kinematics which is characteristic to parallel mechanisms. These issues make programming and trajectory planning harder than for other architectures. Another disadvantage is the limited workspace and a short vertical stroke of the end-effector – essentially, the workspace of the robot is planar, not volumetric, the vertical stroke of the end-effector being used only for lifting the parts from the base plate. The approach of placing a third vertical axis at the end-effector level is suitable only with a short stroke, having the disadvantage of putting additional loads on the robot arms and having low stiffness levels. A longer vertical axis with a more rigid structure should be integrated before the five-link mechanism.

As it can be observed from the measurements, the main advantage of this robot architecture consists of high precision and rigid structure. Also, having a parallel configuration, the mechanical structure is very stable and capable of high speeds, which makes the robot suitable for pick-and-place operations.

7. References
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