A H-Scara Mini Robot - a Dual Parallel Kinematics Mini Manipulator.

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Abstract

This paper represents a H-Scara mini robot and an assembly cell where it is used. The robot is targeted by size and other features to fit into the desktop and micro Factory concept developed by Tampere University of Technology (TUT-μF). The robot has four degrees of freedom. It is a combination of two parallel kinematic structures, which are connected into series. This way the moving mass has been reduced, reachability of the robot extended as far as possible and workspace kept as clear as possible from wires and other mechanical parts like motors. TUT-μF is a concept defining modular reconfigurable assembly system for desktop and micro factories. This is achieved through specifying system architecture, module dimensions, interfaces and other aspects of the concept. This way the modules can be easily and quickly integrated as functional micro manufacturing system. The presented robot is intended to be one module fitting in the concept and to demonstrate at the same time the features of the TUT-μF concept.

1 Introduction

This paper represents a H-Scara mini robot and an assembly cell where it is used. The robot is targeted by size, interfaces and other features to fit into the desktop and micro Factory concept developed and presented by Tampere University of Technology / Department of Production Engineering and it is shorten as (TUT-μF) [1]. TUT-μF is a concept defining modular and reconfigurable assembly system for desktop and micro factories [1]. This is achieved through following the specified system architecture, module dimensions, interfaces and other given aspects [2]. This way the modules can be easily integrated together and configured as functional micro manufacturing system. The modules are also aimed to be as autonomous as possible including to the same housing all components like controls, amplifiers and actuators. Other examples of suitable modules for the concept can be found from [3, 4].
The concept and the represented robot module targets to reconfigurable manufacturing system for desktop manufacturing domain. The fast and reliable reconfiguration is important for the quick adaption of the manufacturing system into new requirements. It will be as well true for new products introduction process and enabling fast time to market. Reconfigurable system and standardised interfaces are on their behalf there to ensure the validity of the investment and enabling long life cycle for the manufacturing module.
The robot itself is constructed from two parallel kinematic structures, which are connected in series. It is targeting mainly to pick & place type of assembly or simple manufacturing processes using a tool like glue dispenser. It has a standard end effector interface available where any compliant tool can be quickly mounted on. The reach of the robot is very wide. This enables a conveyorless production flow or like in our case the component feeder is located to the extended workspace of the robot.
The paper is constructed into following chapters: Chapter 2 represents the overall construction of the robot including the detailed design and workspace. Advantages of the proposed construction are discussed. The case product and the assembly process performed by this workstation is introduced in ch. 3. Chapter 4 presents the kinematics of the robot and related issues. Ch. 5 represents the control architecture and related issues and finally chapter 6 concludes the paper.

2 Construction

The overall size of the robot cell is 200 x 300 x 400 mm (width x depth x height) (**Figure 1**). It is constructed from four modules, which are described later in details.

2.1 Cell Architecture

The H-Scara robot follows the TUT-μFactory architecture and modularity. The cell illustrated in Figure 1 is configuration of four main modules. The robot "stack" consists three of them - the base module (bottom), robot module and controller/vision module.
The base unit is an independent unit having its own controller controlling the activities at the base module. It has TUT-μFactory cell interface at three sides to connect with other cells and one TUT-μFactory process interface at top

of the module to connect process units [2]. Visible in Figure 1 are auxiliary process modules like tray feeders, turn unit and assembly jig at this time. All of them are controlled by the base controller.

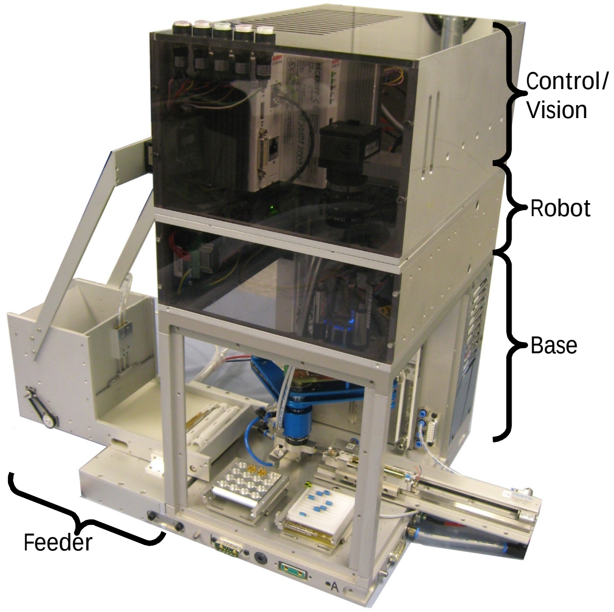

Figure 1: The assembly cell - H-Scara robot and feeder with the case product.

The robot module is the process module at the middle of the stack and it is also the focus of this paper. This module contains the manipulator itself, its amplifiers and required input/output (IO) interfaces. It has a body frame which creates the stationary part of the module and it has two times the process interface - one connecting it to the base module and one offered at the top of this module for additional processes modules. Both the module body and manipulator itself extends to the volume of the base module as illustrated in **Figures 2** and 1. Manipulator has the standard end effector interface available for enabling quick exchange of end effectors like grippers.

The third module is the controller and vision module. It is located on top of the robot module and it has the process interface only at the bottom. The module takes care of controls of the robot (through fieldbus interface enabling the communication between these two modules) and the main level controls of the cell itself. It contains the camera(s) for the vision system. The vision logic is executed also on the very same controller. Some buttons are available for operator human machine interface (HMI).

The feeder is the fourth module and it is connected at the left side cell interface of the base module. Feeder module is independent unit feeding components to the assembly process. It can perform autonomously the feeding once request comes.

2.2 Detailed Robot Construction

The robot has four Degrees of Freedom (DOF) parallel kinematic manipulator (PKM). It is constructed from two parallel kinematic structures, which are assembled in series. This is illustrated in the Figure 2. The first parallel kinematic part is a belt driven H-structure that moves the manipulator in XZ plane (axes X_H and Z driven by motors M1 and M2). The second structure is a parallel scara type -structure attached to the moving body of the H-structure. The scara is construction of four parallel kinematic arms with equal link lengths. The scara structure moves the end effector in XY plane. The axes X_S and Y are driven by motors M3 and M4 respectively. In the end tip there is rotation axis W, which can turn the end effector interface into unlimited rotational positions (W driven by M5). The end effector is attached to manipulator through standard ISO/DIS 29262 size 20 interface [5]. The W axis is hollow so that e.g. camera can look through it and observe the assembly process. The end effector has available two pneumatic lines and four electrical signals, which are pulled through specific construction to enable the unlimited rotation.

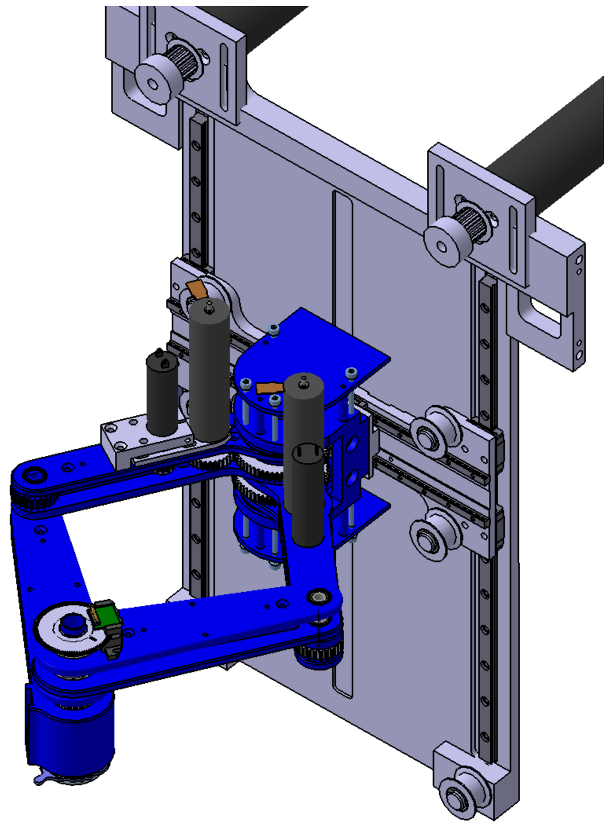

Figure 2: CAD-model of the H-scara manipulator. The belt driving the H-structure is not visible, only the belt pulleys.

The design principle followed has been to keep the workspace as free as possible and work envelope as large as possible including the possibility to access neighbouring cells. These requirements have lead further to locate

all possible mass out of the moving part in order to make the robot as lightweight and visibility as good as possible. Not all motor mass has been possible to be located out of the robot structure. In these cases they and other mass have been located as close the body as possible answering the given requirements.
These requirements and construction makes it possible to achieve high speeds and accelerations with relative tiny motors and amplifiers. At the same time as the construction is kept lightweight and moving masses low, the speeds and accelerations are achieved with smaller motors. These all can be summed up by efficient process operations (short cycle time) and reduced energy consumption. These are the main objectives of the desktop and micro manufacturing together with the size of the process equipment.

2.3 Workspace

The work envelope of the robot is ∼400 x 160 x 130 mm as illustrated in the **Figure 3**. The work envelope is combination of: firstly the rectangle in XZ plane produced by the H-structure limiting to the range of the guides and secondly the XY plane of the parallel scara structure, which is at outside a half circle with radius ∼R and at the inside two parallel half circles with radius of ∼R/2, where R is the farthest extend of the scara structure. The final workspace is the sum of the two areas/spaces.
One driving force of the manipulator design has been the possibility to serve the neighbouring modules in the TUT-μF concept. The manipulator is capable to extend to the workspace of next modules and manipulate objects there. This behaviour can be utilised by e.g. replacing the conveyors and saving some workspace for other purposes.

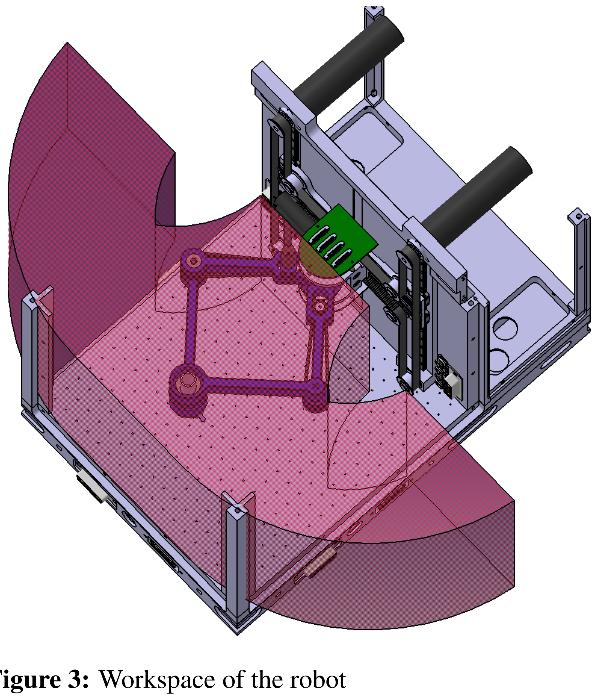

Figure 3: Workspace of the robot

3 Case Application

The case application for this assembly cell is an assembly of a gas detection sensor. The Figure 1 illustrates the assembly process. Four parts are joined together during the assembly - a) two plastic frame parts, which are creating the body of the sensor; b) detector in a metal package; and c) light source (lamp). The parts are glued together with instant glue. Other joining processes were evaluated during the project like laser welding and UV-cured glues. The following cell will have another robot that is used for dosing the glue to the assembled parts.
The H-scara robot takes care of manipulation of all parts. It has a vacuum gripper, which can handle all parts used in the assembly. The gripper has two different suction cups, which are used to handle different parts with best possible grip. The complete assembly process is as following. Machine vision is utilised for recognising the frame part at correct orientation (sensor interior at upside) from the feeder. Vision system calculates the position correction for the object and passes it to the robot. Robot picks and places the frame into assembly jig. Then the robot picks the next detector from tray, takes it to the turn unit and re-picks it after turned and assembles it to the frame in the jig. Meanwhile the glue is dosed to the detector and light source assembly positions. Next the machine vision is used for getting the pick position for the light source. The robot picks it and assembles on the frame. Again the second robot doses the glue, at this time to the frame itself. The robot picks the second frame part from the feeder with the assistance of the vision system, but this time the sensor interior pointing down. The part is placed on the assembly and cured. The finalised assembly is taken out of the cell by moving the jig.

4 Kinematics

The kinematics of the robot is presented in the following chapters. This is divided in three separated cases - H-structure, scara structure and rotation of the W axis.

4.1 H-Structure

H-Structure is fixed to the module body and provides the XZ movement. The H-structure is illustrated in **Figure 4**. The movement is created with two motors that are connected through a single loop tooth belt and the belt is fixed at one point to the slide moving on the guides mounted on the beam (The blue triangle in fig. 4). The beam itself is running freely on other guides.
When the both motors are driven into same direction only the slide is moving and the beam holds its position. The Figure 4 illustrates with the green arrows the positive X_H movement when both motors are running counter clockwise (CCW).

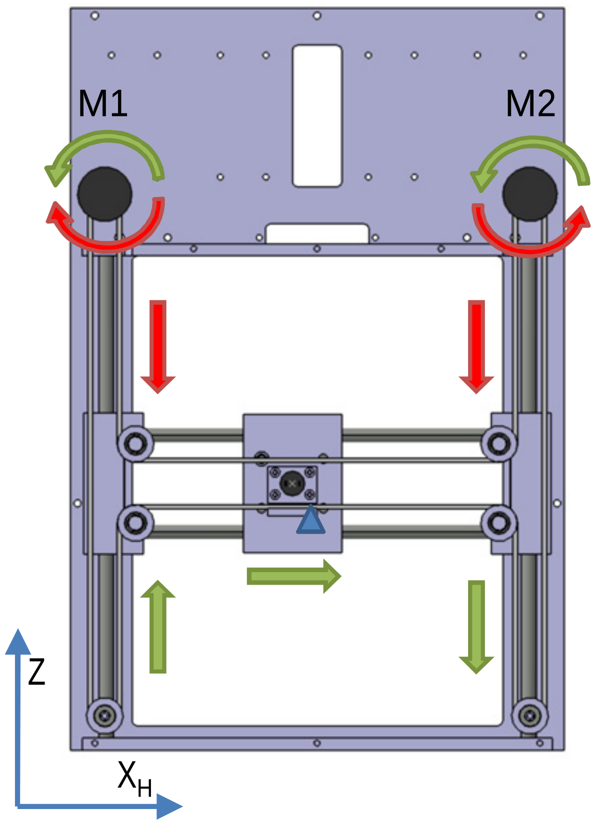

Figure 4: The H-Structure: XZ plane movements by M1&M2. View from front.

On the other hand, when the motors are running opposite direction of each other the slide is keeping its position and only the beam is moving. The negative Z movement is produced, when the M1 is moving clock-wise (CW) and M2 into CCW (Figure 4: the red arrows).
The both axes are having both indirect and direct feedback. Indirect feedback is measured from the rotor angle of motor by use of pulse encoders on motor shaft and direct feedback from two linear encoders with resolution of 1μm.

4.2 Scara Structure

The base of the parallel scara structure is fixed into the moving slide of the H-structure. The scara provides the movement in the XY plane. It is a bit more complicated than the H-structure. The scara structure consist of four connected links and two motors turning the two links connected to the base. These links are called as arms. The structure and associated dimensions and angles letters are illustrated in the **Figure 5**.
The trigonometric equations are used to model the forward and inverse kinematics of the robot. The arm angles a/α and b/β are used to calculate the diagonal (D) and root angle (g/γ). These are used to further calculate the position of the end effector (X_S, Y), and vice versa for the inverse kinematics from (X_S, Y) to (α, β).

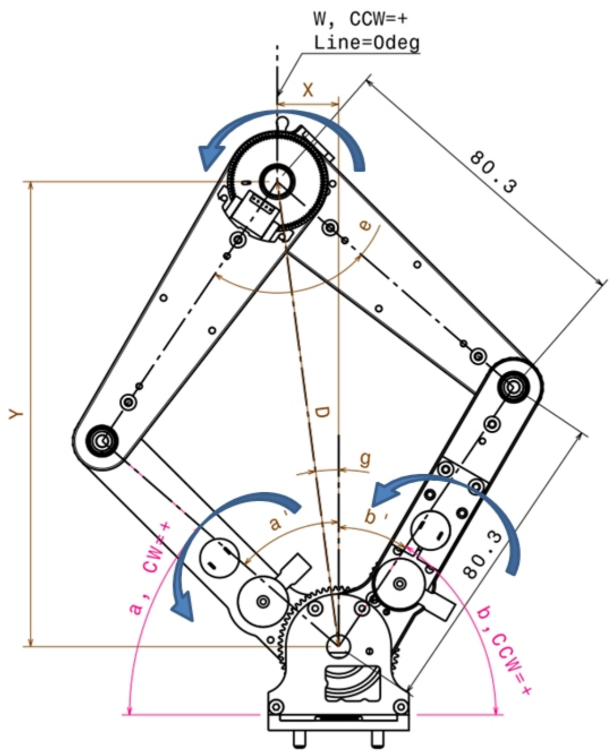

Figure 5: XY plane movements by parallel scara structure driven by the motors M3&M4. Illustrated is also the rotation of End effector (W-axis). View from top. Base located at bottom.

The angle of the arms are measured directly with rotary encoders with resolution of 0,005deg (or 18"). Due to reduction of wiring and selected motor type the motors are not having second encoders on their shaft, which produced some trouble as indicated later.
In many cases the arms are not connected on the same axes on the base but they are having some distance in order to simplify the design like [6, 7]. In our case the both arms are joining in the base on the same coincident axis. This is to reduce the size of the base and to provide larger reachability for the robot. The represented construction in Figure 5 is the third prototype and fourth is on drawing board. The difference between versions is on the turning mechanism and actuation. First one was driven with worm gears, where the backlash was fair too large. Second was implemented with tooth belt, but in this case the belt was not durable enough. The third (present status) is slight modified from the previous so that the belt is changed to cogwheels. Again the issue of the backlash arises, which has led us making the next design iteration, which hopefully will provide final solution and satisfaction.

4.3 Turning Axis W

The turning axis W is located at the end of the scara structure. It rotates the end effector interface. The construction of the axis is made so that maximum visibility and minimum volume is consumed at the end of the parallel scara;

end effector should have maximum rotation. Therefore the driving motor is located to arm link close to the base of scara structure, the W axis is hollow so that camera can look through it to the tool central point (Figure 2). End effector has unlimited rotation due to novel lead-through construction at least by size and compactness.
Angle of the W axis is directly measured at axis with incremental pulse encoder at resolution of 0,18deg (or $\sim$11'). The axis is actively compensated to maintain the orientation in the base coordinate system during the execution. This is required because the measurement is affected by the link angle (e/ϵ). Scara's root angle (g/γ) and the set up angle W are also affecting the control of the W axis and are part of the compensating function.

4.4 Issues

The robot is giving good and promising output, however we still have some issues. The accuracy of the H-structure is good and outperforms the requirements for this specific case application. But the accuracy of the parallel scara is poor due the backlash in mechanics and because of the measuring/control method used. If same kind of measurement and control configuration as we have used for the H-structure would have been possible to be used at scara part then the result would have been a bit better.
Bending and non-rigidity of the parallel scara in Z direction at the end effector will also cause problems in some cases. Especially when the assembly or process requires forces like pushing. The next version of scara design improves this section too by strengthening the rigidity of the elbows and other joints of the scara.
Even amount of wiring and tubing coming to the moving parts has been limited and optimised, it still creates challenges to be solved. There is quite a bunch of wiring needed to be delivered to the parallel scara, because it is completely moving in the XZ plane by the H-structure. Also all wiring going into the end effector tip of the scara needs to make first a middle stop at the base of the parallel scara before reaching the final destination. Together with the small size of the robot and compactness of modules it does not help with the wiring issue. The cut diameter of each wire has been also reduced to minimum. This will create other problems for getting the signalling or motor phases properly through and/or with enough current.

5 Controls

The current implementation bases on industrial controllers, which is not the perfect match for the miniaturised application like this due the "large" volume of such devices. However the advantages of standard hardware and software, easy modular IOs with large variety, tested and proven hardware eases the development cycle so radically that the size was neglected this time and focus was placed on the mechanical construction and the case application itself.

Despite the fact that mainly commercial components are used for controls, still the application shows novelty from compactness and autonomy. All controllers, amplifiers and actuators are fit in to the modules represented in Figure 1. There is no external controller and/or amplifier at size of the robot itself (or even larger) located next to it, like is the case still most often, but all required components are fit inside the modules they serve at. This supports and is one of the main points of the TUT-μFactory architecture and concept.
The cell requires only some external inputs to the system. These are electrical power supply of 24V DC, pressured air and optionally ethernet. The base contains even multi port switch for ethernet to redistribute it to next cells and process modules.

5.1 Control Architecture

The control architecture used at the workstation is illustrated in **Figure 6**. It follows the module autonomy and boundaries as well as possible. Over all module interfaces are passed through power supply connections like 24 VDC and pneumatic air; communication ethernet (100BASE-T); and in some cases additional communication (like fieldbusses on ethernet and/or twisted pair based medium) or digital signalling channels like handshakes for product exchange over module boundary.
The base is completely independent unit with its own controls. Control requests for it are communicated through standard ethernet. The robot module has all its amplifiers and IO modules on board, only the controls are distributed to module above because of the space issues. These two modules are connected together through fast ethernet based fieldbus. The controller module on top of the stack is providing the machine vision operations including the cameras and required SW applications. It is also hosting the HMI through physical buttons and screens. The HMI screens and applications are available through either remote desktop, web pages (server inside the controller) or through use of dedicated integration application communicating with the controller. The two latter are especially interesting through the use of small portable terminals like Nokia 770 internet tablet [8] or Nokia N900 [9], which can offer innovative HMI for such desktop manufacturing application. This way a tiny portable device can be used to monitor and configure the workstations. The size scale of manufacturing and monitoring/configuration device are at the same handy and portable range.

5.2 Control Application

In this case the off-the-self control components were used. This is not the optimum solution in size and feature wise as these components are bit too large and bulky in size for desktop factory application and may give features which are not utilised. But on the other hand they offered a compromise by time, effort and performance wise. Therefore

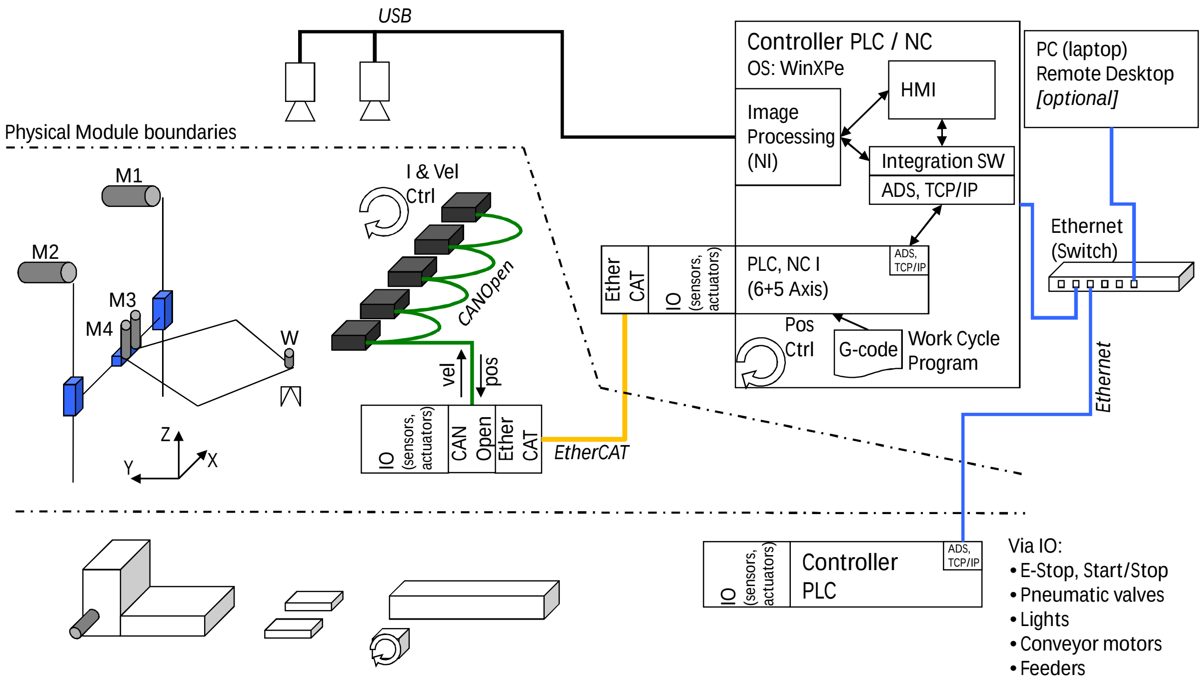

Figure 6: Control architecture of the cell.

well tested industrial tools and components were possible to be utilised. Letting us to focus more on the mechanical design and construction of the robot, than designing the electronics for the application. However to point it out for the final commercial application of desktop factory, the dedicated control electronics HW is most likely a must. Or at least the size of commercial components needs to radically be reduced.

The selected control platform offered for application use a numerical control (NC) over a programmable logic control (PLC), running on a PC architecture and having Win XP embedded OS. The robot itself has five real axes to be controlled and the final application included on top of this six virtual axes, which are used to mix the desired input axes. On other words, the virtual axes are used to implement the kinematic transformation models, so that user can input e.g. X and Y in base coordinate system and these values are automatically transformed e.g. position control of all motors moving the scara structure.

The user interface for the manufacturing application point of view is G-code (used for e.g. machine tool programming). User can program the desired work cycle through this code and he/she does not need to touch the axis, NC or PLC code at all. The G-code includes specific commands for auxiliary devices like end effector, feeder and process devices called M-codes, which are application specific. There can be several different NC codes uploaded on the controller and user just selects which is executed at very time. This can be even automatised in case automatic material flow control is implemented through use of technologies like escort memory or barcode system.

5.3 Control Challenges

From the control point of view the main challenges for this application has been the mechanical backlash combined with the measuring and control method in use; Kinematic transformations and use of virtual axes; Duplicated X axis; and difficult shaped workspace entangled with kinematic limitations. These are discussed next more in details.

The gear backlash at scara structure is already discussed in previous chapters. In addition to those from control point of view the limitations of amplifier-motor-encoder package and configuration played some role. It limited the configuration so that the encoder's index pulse and hall sensors on motor shaft were not possible to be used. The first affected to the homing procedure and the second on the performance and wellness of the control of these axes.

Kinematic transformations of the robot and use of virtual axes to implement them were challenging, but in nice way. These issues are solved and neat solution is presented. The solution used six virtual axes and five real axes to control the robot and implement the kinematic models. User sees the robot as cartesian one and can feed the target points accordingly.

The duplicated X axis caused some additional work as the robot has two X axes - H-structure X_H and scara X_S. This issue is solved at this stage so that user gives in the G-code the position for X and X_S i.e. the final end point and what portion of it is made by the scara structure. The model calculates the set point for X_H. In future an algorithm can be developed for solving and optimising the X_H and X_S directly from the X with the help of the kinematic model of the robot. This will ease the work cycle programming

quite much.
One issue is the difficult shape of the workspace. The process developer has difficulties to understand where the unreachable positions of the robot are (Figure 3). These needs to be taken into account when making process device layout design or when programming the work cycle. E.g. the linear path connecting two sequential positions in space shall not go through unreachable space/position. This leads to the necessity to use intermediate "safe" positions to bypass the limited space. As example this will be the case when the robot is extending to the space at sides. Also the kinematic structure itself causes some limitations, which needs to be kept in mind. The scara has an example certain limitations for the angles like collision of arms and as the user commands are coming directly as positions in the base coordinate system these limitations needs to be implemented into the kinematic model. Checking these limitations remains as future development. All these mentioned problems can be avoided by using mathematical model or simulation for checking the NC program in advance before execution. This can alert if the user is commanding the robot to or through illegal space or if user is commanding the robot out of its reach.

6 Conclusions

The paper represented a compact desktop sized novel mini robot, which is a construction of two parallel kinematic structure in series. The robot has large work envelope especially at sidewise, which makes it perfect to TUT-μFactory concept. The robot is an independent process module, which can be integrated or (re)configured in seconds to the required system configuration. It brings with it in same housing all required controls, amplifiers, IOs and actuators representing truly integrable module in desktop size. The module needs externally only 24VDC supply, pneumatics and ethernet communication.
The first experiences with the robot and its case application has been made and they show the potential of this kind of robot. However they also highlight well the challenges existing at this size class like wiring&tubing problems; selection of right feedback&control methods; design, manufacturing and assembling problems as components are getting tiny and sophisticated; scaling down effects like relative tolerances are close the same, but absolute tolerances are at different magnitude (e.g. gear backlash). Despite of these challenges the robot is looking promising tool for this kind of assembly and manufacturing applications.

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