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Configuration Support and Kinematics for a Reconfigurable Gantry-Tau Manipulator

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Abstract— **Affordable and competitive industrial automation is of key importance for small and medium enterprises, in Europe and elsewhere. A key factor is the introduction of new robot automation concepts that ease fast deployment and extend available task repertoire. The Gantry-Tau manipulator is a new robot concept. In contrast to other parallel kinematic manipulators (PKMs), it has a large working range. The high stiffness makes it ideal for a wide range of tasks such as grinding, deburring, and cutting.**

An additional aspect of such a PKM is the modularity, which in this work has been studied in terms of possibilities for assembly and mechanical reconfiguration at the end-user site, integration of such a kinematically different robot with a standard industrial controller, and new needs for methods/tools to support simple (re)configuration. What is needed for fully utilizing the modularity of the concept in typical SME manufacturing scenarios?

A range of software tools and methods were found to be useful and necessary for efficient engineering and integration. For experimental evaluation, a full-scale prototype robot was designed and built, the kinematic software was developed and integrated into the ABB kinematics software, robot CAD software was adapted to the configuration needs, and both simulations and physical experiments were carried out. Our findings make us believe that enhanced software tools should be integrated on a higher symbolic (or meta-) level to better support transformation of data and code generation, but also that the Gantry-Tau type of robot (with adequate software support) will bring a new dimension of flexibility into SME manufacturing.

I. INTRODUCTION

New low-cost and flexible robot concepts are needed to fulfill the needs of small- and medium-sized enterprises (SMEs) in manufacturing; SMEs depend on their ability to cost efficiently produce customized products, and the use of manual labor is common to accomplish the required flexibility. To maintain profitability on a global market, there is a desire to have robots that in an efficient way can assist human workers. This would require robots to be much more flexible to configure and use, and in many cases much more stiff in the sense of motion compliance compared to traditional industrial robot arms. The Parallel Kinematic Manipulator (PKM) with Gantry-Tau structure [2] has been proposed recently to accomplish a low-cost stiff and flexible robot. The Gantry solution provides a larger working range than other PKMs do. The Tau variant provides an open and accessible work space, which is for example not possible with the linear Delta version.

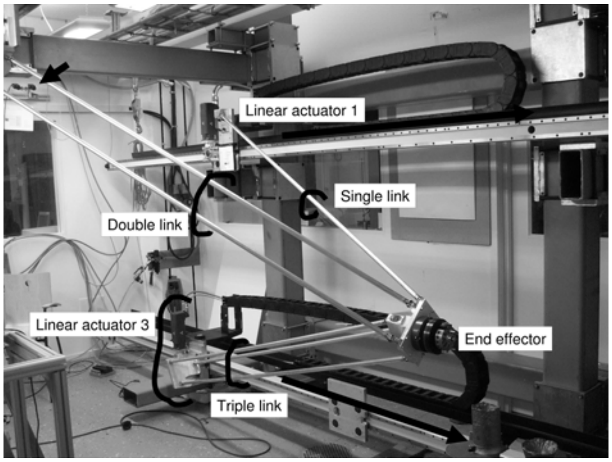

Fig. 1. Prototype 3-DOF parallel robot with Gantry-Tau structure built using a modular framework carrying Güdel linear actuators. The links shown in the picture are controlled through an ABB IRC5 industrial robot controller. Note that the links are not dimensioned for industrial usage. The end effector carries devices for collision protection and tool exchange (cabling for the wrist not included in picture). To the upper left can be seen cameras to be used for signature calibration.

Opposed to traditional serial/articulated robots that come as an optimized unit from the robot manufacturer, a Gantry-Tau PKM can be assembled at the customer site and reconfigured to meet various task requirements, without loosing stiffness or speed if reconfigurations are within reasonable limits. Fig. 1 shows our prototype Gantry-Tau. The robot consists of three linear actuators working in parallel with arm links

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connected to the robot wrist using the Tau structure. Both the robot and the framework carrying the robot are built using modular components to ease fast deployment. Arm lengths can easily be changed by replacing arm links, and the linear actuators can be moved in space by adjusting the framework, thus easing reconfiguration. The overall design and kinematic configuration needed when assembling at a customer site is related to the engineering that has traditionally been done at the robot manufacturer site, but with the increased modularity and the mechancially not redundant link system there is now an opportunity to base the design less on the limits of robots from robot manufacturers, and more on the requirements of the end-user application.

A key property is the usage of a standard industrial robot controller. The Güdel company [7] has experience in integrating their modular robotics components with ABB robot controllers. Therefore, an ABB IRC5 controller was chosen together with Güdel linear actuators to form the core of the prototype. Then, in cooperation with ABB, PKM kinematics was developed for and integrated into the IRC5 system.

It is important to support the new configurability and modularity in robot simulation and programming tools. For end user testing, a PKM work-cell will be built in a medium-sized foundry company (Norton Cast Products Ltd[1]), to be used for cutting and grinding operations. Simulating the process is necessary in order to dimension the PKM for the task. A configurable Gantry-Tau simulation has been developed for a robot tool that targets end-users in the work-cell planning phase, and together with tools necessary for configuring the kinematic structure of the robot at this phase[2] it provided the necessities for the initial planning in the foundry work-cell scenario.

The rest of the paper is organized as follows: first issues regarding PKM kinematics and its application in a controller are discussed. Then the support in end-user tools is discussed. The article concludes with further perspectives and future work.

II. GANTRY-TAU KINEMATICS FOR ABB IRC5

A Gantry-Tau robot (Fig. 2) consists of three parallel prismatic joints moving carts on tracks [7]. The three carts are connected via links to a wrist mount. The six links are clustered into three groups (arms), with one, two and three links, forming the Tau structure. The links are connected to the cart and wrist mount through passive spherical joints (Figs. 2, 3). The links belonging to the same cluster form parallelograms.

A. 3-DOF Kinematics

Gantry-Tau kinematics for 3 degrees of freedom has been implemented in the ABB IRC5 controller (within ABB).

Fig. 2. Table-sized Gantry-Tau prototype shown at the Scandinavian Technical Fair (Stockholm, 3-6 October, 2006). End effector, linear tracks, and gearboxes manufactured inhouse. Drive systems from the Faulhaber Group [6]. Robot controlled from the Visual Components 3DCreate tool (laptop).

Fig. 3. Picture showing arm links dimensioned for industrial usage (with wrist mount).

The Gantry-Tau kinematic solution for 3 degrees of freedom is described in [8]. In contrast to the case for serial manipulators, the forward kinematics problem is the more difficult problem to solve for PKMs. The 3-DOF forward kinematics solution assumes parallel prismatic joints and a fixed orientation of the wrist (which is guaranteed by proper placement of the links in the Tau structure). The problem can then be reduced to a stepwise geometric solution where first the intersection of two link clusters is calculated and then the resulting circle is intersected with the third link cluster. Two solutions exist and a configuration state is needed to decide which one is valid. The forward and inverse kinematics solution can thus be represented as

$$\mathbf{q_x} = f_3^{-1}(\mathbf{x}, \mathbf{s}, \mathbf{c}) \tag{1}$$

$$\mathbf{x} = f_3(\mathbf{q_x}, \mathbf{s}, \mathbf{c}) \tag{2}$$

where the joint positions $\mathbf{q_x} = (q_1, q_2, q_3)$ are related to a tool center point (TCP), position $\mathbf{x} = (x, y, z)$, and parameterized by a configuration state (solution selection) c, and a structural parameterization $\mathbf{s}$. As the configuration state resulting from direct kinematics is not related to the inverse kinematics configuration, c is defined to include both kind of configuration states. The kinematics solutions have been

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[1] Norton Cast Products Ltd, Capital Steel Works, Tinsley Park Road, Sheffield, South Yorkshire, UK.

[2] Configuration of dynamic properties and dimensioning of elastic properties of components were not considered in this tool in this phase.

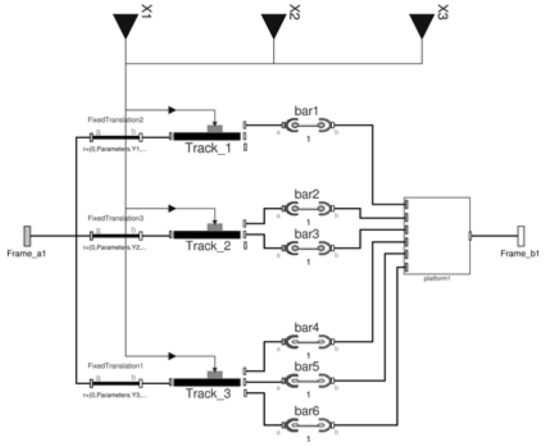


Fig. 4. Modelica model of forward kinematics with elements for track positions, tracks including the carts, links and platform (from left to right); the upper part of the model contains input blocks for the 3 cart positions and the left- and rightmost block designate local coordinate frames.

implemented in Matlab and C for control purposes, and in Maple and Python [16] for simulation and analysis purposes.

B. Kinematics descriptions

To capture and support the modularity and flexibility of the GT-PKM as needed for manufacturing SMEs there is a need for a common higher-level kinematic description that can ease implementation of new software tools, methods, and algorithms. Symbolic representation of kinematics is necessary for developing methods for calibration and configuration such as identifying geometrical and dynamical properties of an assembled robot.

As an example, a higher level kinematic description would considerable ease integration efforts between applications. An ongoing experiment aims at integrating two applications featuring discrete event simulation of work-cell layouts (3DCreate [19]) with automatic program generation (Rinas Weld [10]). A common higher-level kinematics description enabling the two software environments to share robot geometry and kinematics would considerably ease the integration effort.

To this end, the Modelica language has been tested by using it for analysing kinematics. Modelica [13] is an object-oriented modeling language. Dymola [5] by Dynasim is a commercial implementation of Modelica, which is used in this work. Figure 4 shows a Modelica model of the Gantry-Tau robot. Two different kind of models have been implemented to model direct as well as inverse kinematic behaviour. The Modelica Multi Body Library models kinematics and dynamics (kinetics) of rigid body systems. An advantage of Modelica is that mechanical models can easily be extended with models from other domains, e.g., a controller or an actuator for the PKM. Together with additional files provided by Dynasim, C-files generated for simulation can be used for hardware-in-the-loop simulations, e.g., for control of the robot.

This, together with other experiences from manual implementation of a GT kinematic solution in C for ABB IRC5, implementation in Maple with code generation towards Visual Component specific Python, and modeling and analysis in Modelica points clearly towards a need for a common kinematics description valid across both controllers and tools.

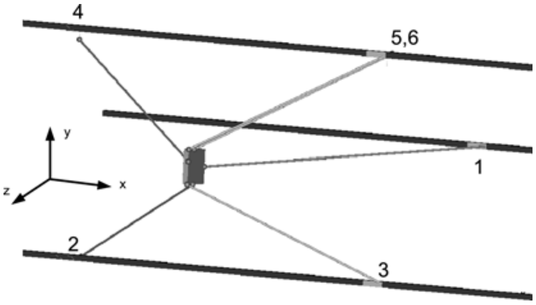


Fig. 5. Extension to 5-DOF with two additional carts.

C. Higher degrees of freedom

Ongoing work aims at extending the kinematics included in the IRC5 controller to higher degrees of freedom. Two different ways of extending the existing 3-DOF robot to 5-DOF are conceivable. First, mounting an active wrist with two rotational DOFs on the existing wrist mount has been considered. A second possibility is to add two supplementary carts on two of the tracks and have the six links distributed on five clusters.

For the first case, an analytic solution of the kinematics problem is easy to derive. In this case, position and orientation can be regarded separately. For forward kinematics, first the platform position $\mathbf{X_p}$ is calculated from the joint positions according to [8]. Then the TCP position $\mathbf{X}$ and orientation $\mathbf{R}$ is obtained by considering only the active wrist with rotation angles $\mathbf{q}_\theta = (\theta_1, \theta_2)$ and kinematic parameterization $\mathbf{s_w}$ (e.g. Denavit-Hartenberg parameters):

$$\begin{aligned}(\mathbf{X}, \mathbf{R}) &= f_5(\mathbf{q_x}, \mathbf{q}_\theta, \mathbf{s}, \mathbf{s_w}, \mathbf{c}) \qquad (3)\\ &= f_2(\mathbf{q}_\theta, f_2(\mathbf{q_x}, \mathbf{s}, \mathbf{c}), \mathbf{s_w})\end{aligned}$$

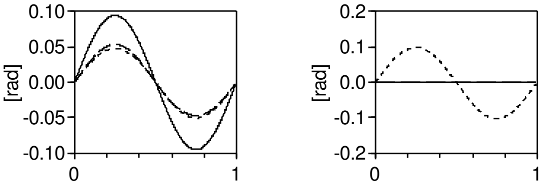
$f_2(\mathbf{q}_\theta, \mathbf{X_p}, \mathbf{s_w})$ can easily be calculated, see e.g. [14].

The inverse kinematics problem can be solved in a similar way.

A problem here might be the implementation of the active wrist that would require extra weight and cabling to facilitate. However, there is full freedom in the structural design of the wrist.

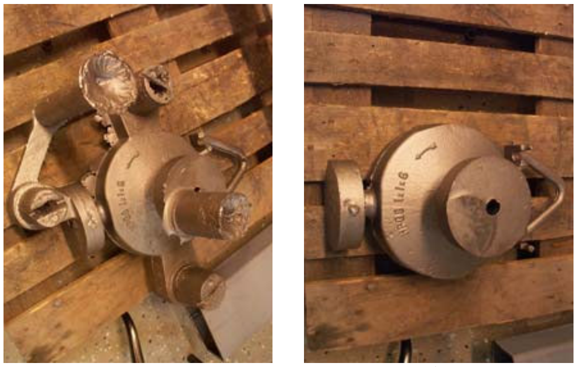
The other solution relies on having 5 carts running on the tracks instead of 3. The advantage here would be that weight is moved from the robot hand to the framework, but the disadvantage is a much more complex kinematics solution together with a severe limitation in orientation freedom.

Simulations are essential to investigate the benefits and limits of such a design. Involving 5 parallel kinematic chains and two rotational DOF, the direct kinematics can hardly be solved analytically, the inverse kinematics are more complex because of the variable platform orientation. This makes



(a) (b)

Fig. 6. Simulation results: TCP orientation resulting of moving link 2 (a) and link 4 (b), successive rotation around x- (solid), y- (dashed) and z-axis (dotted)



(a) (b)

Fig. 7. Foundry workpieces. (a) before cut. (b) after cut.

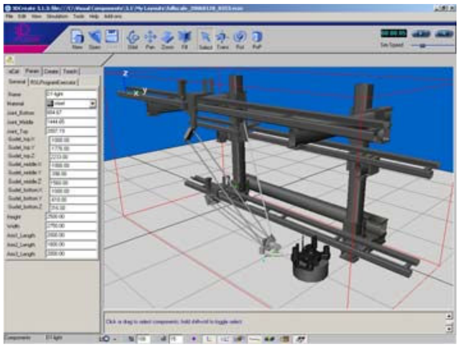


Fig. 8. Prototype SMErobot foundry work-cell using a reconfigurable Gantry-Tau PKM for material removal. To the left are reconfiguration parameters for the modular framework supporting the PKM.

analytical examination of the robot difficult. However, examination is needed. The authors have derived an approximate solution of the direct kinematics using the Modelica language and Dynasim tool.

A first study was to investigate quantitatively the orientation limits of this 5 DOF Gantry-Tau variant. For each of links 2 to 6 (Fig. 5) a movement of the link connected to a separate cart has been considered while the other carts have had a constant position. The rotation angles for successive rotations around x-, y- and z-axes have been studied. Figure 6 shows simulation results for a sinusoidal movement of the separated link with an amplitude of 0.5

Moving link 4, a pure rotation around the z-axis can be performed (Fig. 6). Moving link 2, 3, 5 or 6 separately gives a composed rotation around all axes (Fig. 6 for link 2). Simulation experiences show that rotation limits exist which may vary considerably throughout the work-space. Depending on the TCP position and the considered link, the angular limits arising from moving a single link have values from $\pm 3°$ to $\pm 103°$. These values have been obtained without considering possible angular limits of the spherical joints.

III. GANTRY-TAU CONFIGURATION SUPPORT

The modular design of the Gantry-Tau PKM allows part of the overall design and kinematic configuration traditionally performed at a robot manufacturer site to be exposed as configuration options towards the end-user, thus increasing the robot flexibility towards the end-user application. However, (re)configuration options must be analysed and handled already in the work-cell planning phase for the end-user to benefit from these properties optimally. This calls for reconfigurable simulation models to be included in robot tools together with robot-specific tools for analysing/deriving robot configuration properties (pre-calculated for traditional non/limited-configurable robots and normally available from the robot manufacturer), such as work-space envelope, for comparison to task requirements, and (eventually) synthesising configurations based on robot task requirements.

A. *Task-centric configuration in foundry scenario*

Due to bad working conditions, cutting and deburring in foundry industries is an important robot application. Our foundry scenario is captured from one of our end users (Norton Cast Products Ltd), and considered one of the project key demonstrators for new easy-to-use robot concepts. The application consists of material removal by cutting input metal reservoirs, which are needed for the casting process but not part of the product (compare left and right picture in Fig. 7), followed by deburring. The foundry workpieces come in small batches (estimated 1-10), varying sizes (estimated 10-1000kg), and varying shapes.

Properties considered interesting in the initial work-cell planning stage were work-space envelope (to handle varying workpiece dimensions), reachability of cutting tool towards workpiece, dexterity (for good cutting process), determination of necessary degrees of freedom for wrist (to reduce weight), and determination of the necessity of an external axis for the fixture (to increase reachability). Configuration decisions were to be assisted by simulations performed in a work-cell and factory planning tool. The 3DCreate tool from the company Visual Components Oy [19] is a new tool specifically targeting end-users planning factory and work-cell layouts. The tool offers discrete event simulation and visualization of manufacturing processes together with mechanisms for modeling, packaging, and deployment of simulations. A component model with plug-and-play possibilities allows the end-user to build and simulate factory and work-cell layouts within minutes that can be exchanged

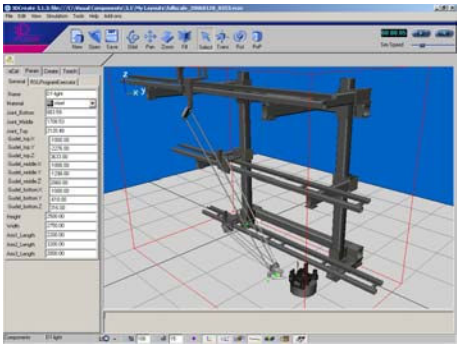


Fig. 9. Gantry-Tau before reconfiguration.

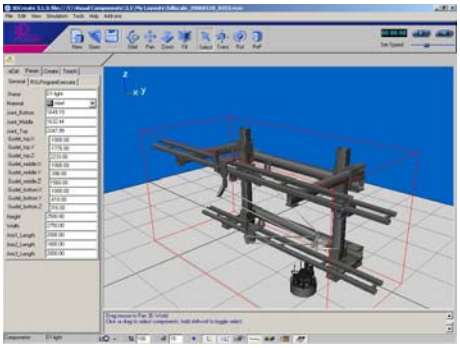


Fig. 10. Gantry-Tau after reconfiguration.

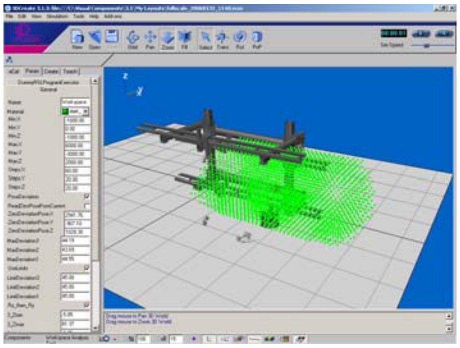


Fig. 11. Work-space envelope for a sample Gantry-Tau configuration.

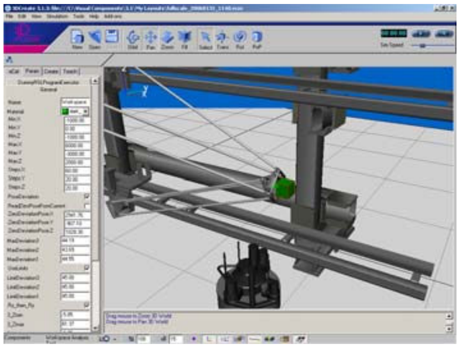


Fig. 12. Work-space exploration end effector mounted on Gantry-Tau robot. The tool implements a simple grid-based algorithm to estimate work-space envelope. Figure 11 shows the outcome of the tool.

by email and analyzed for various properties. An example workpiece was selected (approx. 50kg) to aid decisions in the smaller range of workpieces.

To configure the robot to better fit the task in consideration, a reconfigurable robot simulation was implemented in the 3DCreate tool. For the initial planning a family of work-cell simulations with the robot were then created featuring different wrists (1, 2, 3 DOFs), different fixtures, and different number of external axes (0, 1 DOF). The size of the robot was selected by reconfiguring the robot with ranges of link lengths and track positions to find a good working envelope for the task while adhering to volumetric constraints (room size). Reachability and collision-freeness were confirmed for the example workpiece CAD model by explicitly programming and simulating the cutting process for promising work-cell candidates. This also gave an indication of how the work-cell might perform for other workpiece geometries, although further testing would be necessary. Figs. 8, 9, 10, 11 show one candidate work-cell with robot reconfiguration, selection of wrist and fixture, and result from work-space envelope analysis of one robot configuration (easily covering the workpiece).

B. Virtual tools to ease task-specific configuration analysis

To assist in the initial work-cell planning stage it was important to ease configuration analysis in the simulation tool. In particular, easily accessible methods for deriving robot configuration properties were needed. Later a need for task knowledge in the simulation tool was discovered. Availability of automatic programming for the cutting process would probably have meant significantly reduced time spent on verifying reachability and collision-freeness at the initial planning stage.

Having these needs, and at the same time considering the component model used in the simulation tool, the solution was to create virtual end effector tools containing both tool geometry and process/task knowledge, thereby allowing the tool to automatically program any robot that it was mounted on. Thus, if an oxy-fuel burner tool containing cutting task knowledge is mounted on the robot end effector, it may result in the robot being programmed automatically. Hence, the robot effectively becomes a cutter, that is automatically/manually configured/programmed for cutting operations. The association tool-task knowledge decouples the robot from the task through tool exchange, making it easy to switch between different robot tasks by mounting different tools. This non-robot-centric view[3] differs from the traditional view, where task knowledge is located in the robot.

Two examples of virtual tools were created. Fig. 12 (mounted cube) shows a pure virtual end-effector tool (no representation in the real world) used for obtaining an estimate of the robot work-space envelope for a given configuration. It contains a parameterized robot task (search

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[3] This approach is concurrently being investigated by SMErobot partners Fraunhofer IPA and COMAU.

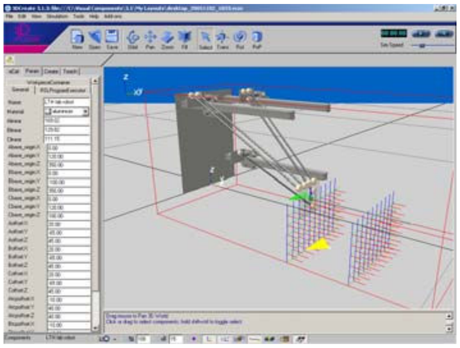

Fig. 13. Desktop version of Gantry-Tau equipped with a fictitious touch sensor and programmed with a search pattern.

volume, sample step) that defines a discrete volume grid search algorithm noting reachability for each visited position in space. The result is stored as a program in the robot containing all reachable points, and may be viewed by the simulation tool (Fig. 11). Fig. 13 shows a touch sensor virtual end effector tool. The tool contains a grid search algorithm to probe the surface of a workpiece placed in front of the robot which can be used, for instance, for analysing reachability and collision-freeness towards a CAD workpiece for given configurations. Unlike the previous tool, the virtual touch sensor may present a real tool, and might even be used in path planning the search for the real work-cell. Eventually, in this particular case, the virtual tool geometry is to be replaced with the geometry of a real touch sensor and moved to the full-scale Gantry-Tau robot. Both tools were created following the component model of the simulation tool and were implemented using the builtin script language (Python [16]).

IV. CONCLUSIONS

The reconfigurable Gantry-Tau PKM is a new robot concept that has the potential to achieve a cost/performance ratio that would make it highly attractive for SME manufacturing. To support reconfiguration, it was experienced that robot simulation and programming tools need to provide aid in terms of reconfigurable robot models and end-user analysis methods. For implementation, 3DCreate provided good support through its component model, plug-and-play capability and the flexible Python-scriptable engine. To increase flexibility, two possible extensions of existing 3-DOF kinematics to 5-DOF were presented.

To aid the engineering in terms of analysis and synthesis of the robot work-cell, a task-centric view was proposed to ease adaption of the robot configuration towards the application. As an example, the work-space analysis tool (implemented in Python as a virtual end-effector) has turned out to be easy to use by other users, knowing nothing about the internals. For robot programming and task configuration in general, a non-robot-centric view was proposed, where task and process knowledge are associated with the end-effector. The end effector also programs the robot, so that by mounting a drill tool the robot becomes a drill and is configurable for drilling operations.

The modularity and flexibility of the GT-PKM, together with the needed toolkits for configuration and task definition, have made us realize that there is a need for a common higher-level kinematic description that can ease implementation of new methods and algorithms. Code generation towards explicit controllers, low-level code, robot models, and other representations is equally important to lower the amount of engineering time needed. Symbolic representation of kinematics and other properties are necessary for developing methods for calibration and configuration such as identifying geometrical and dynamical properties of an assembled robot. Our conclusion is that such an increased level of abstraction is of key importance to fully exploit the increased flexibility, without too extensive engineering efforts.

V. ACKNOWLEDGEMENT

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