

Methods for Evaluating the Functional Work Space for Machine Tools and 6 Axis Serial Robots

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ABSTRACT

The 'boundary of space' model representing all possible positions which may be occupied by a mechanism during its normal range of motion (for all positions and orientations) is called the work envelope. In the robotic domain, it is also known as the robot operating envelope or workspace. Several researchers have investigated workspace boundaries for different degrees of freedom (DOF), joint types and kinematic structures utilizing many approaches. The work envelope provides essential boundary information, which is critical for safety and layout concerns, but the work envelope information does not by itself determine the reach feasibility of a desired configuration. The effect of orientation is not captured as well as the coupling related to operational parameters. Included in this are spatial occupancy concerns due to linking multiple kinematic chains, which is an issue with multi-tasking machine tools, and manufacturing cells. This research presents methodologies to predetermine regions of feasible operation for multiple kinematic chain mechanisms, such as multi-spindle/multi-axis machine tools and industrial serial 6 degree of freedom robots, and manufacturing cells.

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INTRODUCTION TO THE FUNCTION WORK SPACE

Background

The 'boundary of space' model representing all possible positions which may be occupied by a mechanism during its normal range of motion (for all positions and orientations) is called the work envelope. In the robotic domain, it is also known as the robot operating envelope or workspace [1]. A comprehensive set of mechanism structures has been designed and built to fulfill various industry needs for machining, assembly, material handling, material deposition, and so forth. These multi-Degrees of Freedom (DOF) machine tool or robotic structures can be highly complex as there may be redundant joints (serial six axis industrial robots), combinations of rotary and translational axes (machine tools), the translational axes may not be orthogonal (nutating machine tools), and the kinematic chain loops can dynamically change for multiturret, multi-axis machine tools.

In the robotics domain, several researchers have investigated workspace boundaries for different DOF, joint types and kinematic structures utilizing many approaches [2,3,4,5,6,7,8,9,10]. The total workspace of any multi-DOF manipulator is a finitely bounded 3-D space which is topologically complex and challenging to visualize (Figure 1). This region is necessary to define for addressing layout and safety issues.

In this total enclosed workspace, the true reachable region of a manipulator is a combination of various 3-D subset(s), which are impacted by the end-effector orientation and length, which may or may not be mutually exclusive. Consequently, the work envelope based work has limited use as it does not contain relevant information regarding the relationships between the robot, or mechanisms within a system. From a process design perspective, it is important to determine the functional reachability limits for an end-effector.

Many contemporary industrial robots contain solely rotational joints. However, hybrid kinematic structures, consisting of rotary and translational joints, are being realized in work cell configurations, which introduces unique challenges for path planning, and obstacle avoidance as well as the robots' capabilities for a wide range of product / process related tasks.

For autonomous work cells, there are spatial occupancy concerns due to linking multiple kinematic chains, which is also an issue with multi-tasking machine tools. Multi-tasking machine tools can be considered CNC mill-lathe hybrids. They consist of multiple open kinematic chains of translational and rotary joints [11, 12] and may have several valid kinematic chain / axis combinations.

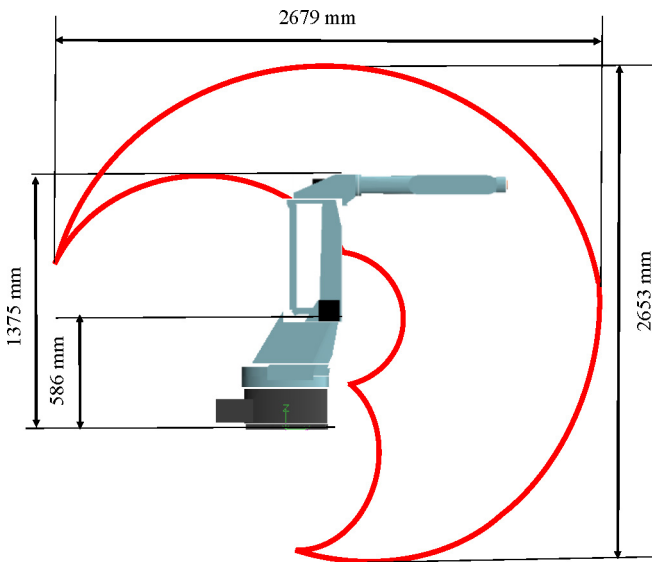


Figure 1. Working range for the Motomen SK 16 - a small multipurpose industrial robot (25kg mass)

These machines enable multiple tool engagement in multiple parts simultaneously, with each tool/ part/ spindle/ axis set combination following its own unique programmed path. These machines minimize the number of manual operations, as well as reduce setup costs and potential quality issues. A single multi-tasking machine tool can completely machine complex parts from start to finish [13]. Modelling the dynamic kinematic chain loops is beyond the scope of this work, but needs to be considered when assessing the feasibility of a path in time and space for these machine families [14].

As the functional operating region is not readily defined by the general machine / robot information [15,16,17], another assessment parameter needs to be introduced to indicate the functional operating work space. Hence, the work window or functional work space is introduced, and is defined as the valid functional space for a configuration to allow a kinematic structure (robot, machine tool, etc.) to follow a path for a set of conditions relating to the system configuration, tooling, fixture location and so forth [18]. A part may be located within the work envelope, but it may not be within the work window. In Figure 2, the encircled region cannot be reached for the 'normal to the base' orientation for the 6R Fanuc robot [19] although the part is within the envelope.

The actual work window conditions will vary based on the part, travel path tool parameters, geometry, machine kinematic composition and the application. For machining operations, the work window will vary for each unique orientation/ tooling /fixture combination. A methodology needs to be developed to define the work window for a configuration, and any potential reconfigurations. The assessment of system elements is necessary in order to examine the feasibility and practicality of a set of kinematic structures in a manufacturing scenario. This does not exist at this time. There is a direct relation between the kinematic structures, their manipulability and constraints, to the work window. Proper assessment of system elements will help in optimization of a system and help in deciding various parameters such as number of degrees of freedom, placement of machines, robots and other supporting mechanisms (in case of a

work cell consisting of multiple kinematic chain elements) and so forth. The goal of this work is to focus on foundational functional work space or work window assessment approaches.

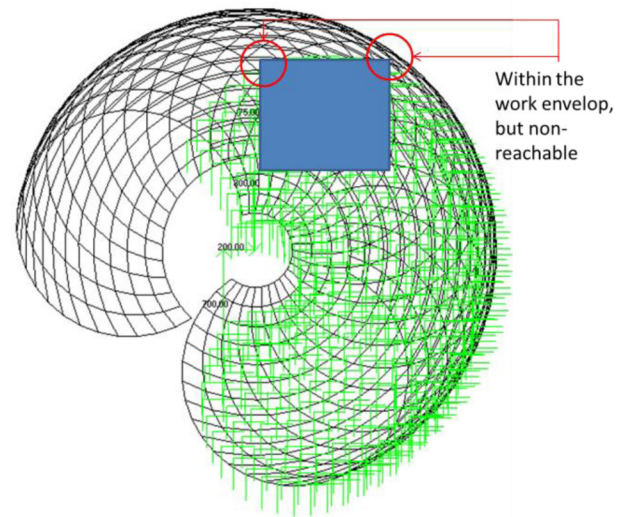


Figure 2. Work envelope and work window for a for the Fanuc M16 Robot for 90 degree (normal) orientation

Research Approach

For both the machine tool and 6 axis industrial robot scenarios, the overarching problem is reduced to a problem sub-set. For the machine tool environments, an appraisal of "primitive" or basic kinematic building blocks is performed and a breakdown of their characteristics is presented. These elemental building blocks are used to create the basic working boundaries using geometric modelling techniques and Boolean operations for more advanced kinematic structures.

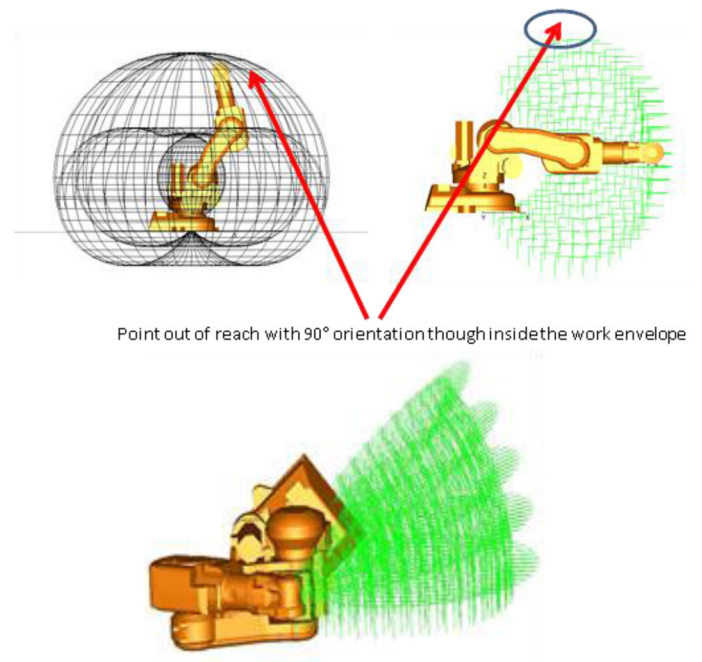


Figure 3. Generation of a 3D functional space region for a normal (90° down) end-effector orientation for a 6 serial axis industrial robot, rotating around Z

A different solution approach is required for the selected industrial robot families (ABB [20] and Fanuc), which is presented in detail. A 'planar' solution is constructed for a specific end-effector configuration-orientation (Figure 3). A 'common' functional space is determined. Then a 3D space is defined for a complete solution by rotating joint 1, as shown in Figure 3. For work cell or complex configuration solutions, a combination of solutions may be required, and is future work.

METHODOLOGY TO DEFINE THE FUNCTIONAL WORK SPACE

Decomposition Analysis for Machines Consisting of Elemental Combinations

'Primitive elemental combination' designs are employed to design milling machines, lathes, routers, coordinate measuring machines (CMM's), and so forth. There are standard machine families (i.e., 5 axis table-table structure) but there are also specialty combinations that are becoming more ubiquitous. There are several basic travel paths strategies that can be employed. The types and typical applications are as follows, and summarized in Table 1:

- The R represents a rotary axis, and the T a translational axis. For this work, it is assumed that axes are stacked orthogonally.
- The coded delineation represents the axis stack, i.e., RT indicates that a translational axis is orthogonally stacked at the end of a rotary axis (Case 2 in Table 1).
- 2 axis (X, Y) travel path motion, which is used for tool less profile machines such as water jet, plasma jet and laser cutting. The work space = work window and is a rectangular surface bounded by the axis stroke limits. The machines are typically a gantry based construction, and is presented as Case 4.
- 2 axis (Z, X) travel path motion + rotary spindle, which is used for lathe machining. This is a subset of Case 4. The axes only move in Z and X, but are swept in a rotary profile)
- 2 axis (X, Y) + Z depth ('2 ½ axis') travel path motion, which is used for additive manufacturing machines. This is trivial as the work space = work window and is a surface bounded by the axis stroke limits, incremented by a specific Δz value. This is a subset of Case 6.
- 3 axis travel path motion, which is used for standard milling machines. The work window is offset from the workspace by the length of the tool and is a cube, also bounded by the axis stroke limits. This is presented by Case 6 or Case 4 in combination with the Case 0, T.
- 3 axis travel path motion and 1 or 2 axis rotary positioning, which is used for standard 4 and 5 axis milling machines, and 5 axis CMMs. These are combinations of Cases 4-6 and 8-10.
- 5 axis travel path motion, which is used for 5 axis milling machines. These are combinations of Cases 4-6 and 8-10.

More sophisticated machines, such as multi-tasking machines, consist of a combination of 3, 4, and 5 axis sub-machines on a lathe frame. The common characteristic of these types of mechanisms is that they can be broken down into basic primitive elemental structures. One kinematic chain holds the tool, the other the part. These elemental structures are combined to create a closed kinematic loop. The reference planes reflect how the axes are physically stacked, and the datum locating points between these elemental structures are used to link relationships to define the usable three dimensional (3D) space. It is readily evident that in many cases the work envelope essentially consists of the bounding stroke positions of the linear or translational axes. The process flow for determining the work window for these mechanisms is illustrated in Figure 4.

When specific subscripts are included, for example Case 8 - *TXRB*, this is used to indicate an axis placed on top of another axis, in the order listed. The *A* axis rotates around the *X* translational axis, the *B* axis rotates around the *Y* translational axis, and the *C* axis rotates around the *Z* translational axis. The workspace of the 2 DOF mechanisms may be a surface, curve or line. Depending on the axis combination and axis stack, the bounding conditions for an axis combination may be a segmented line - i.e., a void exists where the axis/part / fixture is located. The 3 DOF mechanisms usually have a 'solid' region workspace. Again, this depends of the joint type (rotational or translational) and their order in the kinematic chain. The revolve profile consists of the sweep volume of the rotary axis, part, and fixture profiles around the rotation axis.

A collinear Z axis combination for a vertical 3 axis milling machine is shown in Figure 5 (a combination of Case 0, T and Case 4).

In Figure 6, a 5 axis vertical milling machine which is comprised of Cases 5 and 6 is shown. In Figure 7, a horizontal 5 axis milling machine is illustrated, which is comprised of Cases 4 and 9. For this machine, the revolve profile is also displayed.

For step 3 in the work window process flow, the analytical representation for Cases 1-7 is relatively simple, and related directly to the axis limits (all cases) and tool length (Cases 2, 3, 5 - 7). The complexity is introduced when coupling the kinematic chains for Cases 0, R and 0, T, and Cases 4, 5, and 6 with Cases 8-10. Reference planes need to be established to link the axes' ground positions. Along with the axis stack order, the axes travel limits must be defined, as well as the revolve profiles, where appropriate. Set theory and Boolean operations are then performed to couple the fixture and tooling kinematic chains in relation to their bounding geometry.

The addition of the rotary axes immediately reduces the maximum part size that can be machined (Figure 8). This reduction of available work space (or volumetric void) depends on the center of rotation for the rotary axis, its rotational limits, and the axis stack; hence, the importance of being able to generate the revolve profile. The inclusion of the fixture(s) and part(s) modifies the rotary profile for an axis stack located on the table.