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A Kinematic Model for Robot Fixture with Unilateral Constraints

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Abstract

The adoption of industrial robots and collaborative robots (cobots) requires significant development in robot integration. Besides the abundant instructions for programming and improved usability, the mechanical design aspects for robot integration still depend on engineers' individual expertise. This paper provides an easy-to-learn set of models to support the fixture design. It exposes the challenges in modeling unilateral constraints, i.e. detachable contacts between fixture and workpiece, and proposes the concept of Unilateral Constrained Degree of Freedom, which combines conventional degree of freedom and unconstrained movements in one expression. To facilitate the design process of robot fixtures, the paper clarifies the logical relations between movements used for load, constraint, freedom, entry and exit used in a two-step design process. The models presented have been developed and tested during the educational activities at the author's institution.

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Keywords: Fixture; Robot integration; Degree of freedom; Unilateral constraint

1. Introduction

The rise of industrial robots and collaborative robots (cobots) has effectively converted considerable manual operations to automated processes. The development of robot-equipped production requires specially engineered tools, fixtures, equipment, and program for a specific operation, depending on the operation type, workpiece's geometry, and properties. The design of work-holding tools, e.g. gripper and vacuum cups, and fixtures normally requires experienced designers with knowledge and years-long hands-on practice.

The models for work-holding tools and fixtures were mainly developed for machining decades ago. However, these models exhibit limitations in the context of cobot, whose applications differ from machining applications in aspects below.

- Low mechanical loads. Operations that substitute manual work often require low mechanical loads, which do not necessarily require full constraints and clamping as CNC machining.
- Quick entry to and exit from the fixture. The most common pick-and-place task aims at moving workpieces between devices, while no human intervention is involved. Fast and effective engagement and disengagement indicates high productivity. Therefore, no clamping is desirable.

Based on the two observations above, cobot fixture design has exhibited new features below.

- Incomplete constraint. Due to low mechanical load and simple entry and exit to the fixture, cobot fixtures often provide constraints less than 6 degrees of freedom (hereafter mentioned as DoF).
- Constraining and positioning are achieved mainly with contact, while clamping and suction are kept only when necessary.

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1.1. Bilaterial vs. Unilateral Constraint Model

Referring to the example in Fig. 1, let's denote the translational movements with X, Y, and Z in upper case, while rotations in x, y, and z in lower case. Directions are denoted by + and – signs.

Existing kinematic models for positioning the workpiece may claim that the workpiece has only 1 translational DoF along Y axis, by assuming the workpiece remains contact to the five pins. The sustained contact exemplifies bilateral constraints between the pins and the workpiece.

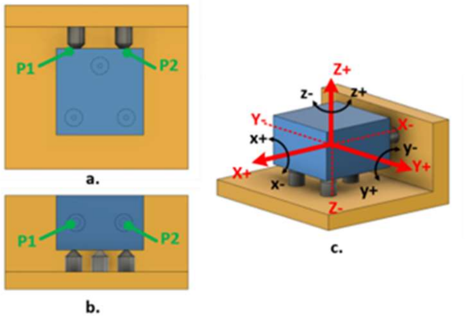

Fig. 1. A workpiece, whose coordinate system is defined in (c), is constrained by five pins.

In reality, constant contact between bodies only exists when retaining forces or mechanisms are available, for instance with the help of magnets or vacuum cups. However, when there is no retaining force to prevent separation, this kind of bilateral constraint model exhibits discrepancies to reality. Unilateral constraint considers the scenario when the body in Fig. 1 still maintains the freedom for moving towards X+ and Z+, when the pins can separate from the body. It is understood that the DoFs in X and Y directions are only relevant in one direction. Furthermore, it is also argued that when one of the pins P1 and P2 can separate from the body, the rotational movements z+ and z- are not restricted, shown in Fig. 2. This situation is exposed in [1], where a clamp is added to hold the workpiece against the pins.

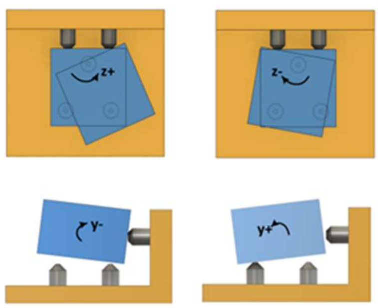

Fig. 2. Rotational movements when one of the pins separates from the workpiece.

1.2. Established Kinematic models for Fixture Design

The models for fixture design can be overviewed in two clusters. The first one comes from a practical view of machine building, especially based on the inventory of positioning, supporting and fastening components [1]. The term degree of freedom literally reflects allowed movements in a 2D or 3D space. Each translation or rotational dimension of a free body contains a positive and a negative movement, therefore an unconstrained body in space has 12 movements [1]. With simple machine elements, for instance straight edges and holes, a fixture deducts a number of DoFs and movements from a free body. This view is easy to understand for design practitioners.

The other cluster of literature focuses on kinematics in rigid body dynamics, where DoF describes the number of independent variables for describing one or multiple bodies' position or movement. It provides an intrinsic mathematical description of the movement. However, these kinematic descriptions can be abstract and challenging for design practitioners with limited understanding in mathematics, not even mentioning contact, friction and separation. Moreover, the classic DoF definition lacks the consideration of contacts that allows only movement in one direction. For example, the workpiece in Fig. 1 has a DoF in X dimension, but this notion does not provide information that the DoF can only move in X+ direction.

Based on the two views summarized above, the author would like to argue the lack of a concept that can accurately and briefly describe the constraints offered by a fixture.

1.3. Value for education

Tasks of robot integration require specially engineered fixtures and tools for specific products. This type of design task normally requires experienced designers with years-long hands-on practice. Moreover, designers in different industries, such as electronics and automobiles, have various best practices inherited and formed throughout their careers. Up to now, in both literature and education, there lacks a unified description and method for robot fixture and tool design.

The increase of robots in manufacturing not only indicates reduced human labor required in production, but also increased human resources allocated to developing, reconfiguring and maintaining robot equipped production. An easy-to-understand set of models and methods will make it easier to up train operators into developers.

1.4. Content of This Paper

Up to this section, this paper has exposed the necessity of models for describing and prescribing kinematic models for fixtures. In Chapter 2, the author will firstly propose a descriptive model for the fixture kinematics that takes unilateral constraints into account. The second part of Chapter 2 offers a prescriptive model for facilitating fixture design. Chapter 3 documents the author's attempt at implementing the proposed models in a workshop with college students and the didactic outcomes.

2. Proposal of Kinematic Model and Design Process

2.1. Proposal of Unilaterally Constrained Degree of Freedom

Following the case described by Fig. 1 and Fig. 2, Table 1 summarizes all the allowed movements under unilateral contact, when a corresponding force or moment is applied. Each "*" sign in the row "Freedom" indicates an unconstrained movement. It is worth noting that the workpiece is free to rotate about all the x, y, and z axes in both + and – directions, although the pivot point varies, when the rotating direction switches.

Table 1. The list of constrained and free movements of the workpiece concludes its UCDoF number.

	Translation						Rotation					
Movements	X+	X-	Y+	Y-	Z+	Z-	x+	x-	y+	y-	z+	z-
Freedom	*		*	*	*		*	*	*	*	*	*
UCDoF	0.1		1		0.1		1		1		1	

Reading from the row "Freedom" in Table 1, the workpiece is allowed to have both + and – freedom in Y, x, y, and z dimensions. Hence, it is claimed that the fixture allows 4 fully unconstrained DoFs, while the rest 2 are partially unconstrained in X and Z dimensions. In this case, the unilaterally constrained degree of freedom (UCDoF) is calculated to be 4.2, where the integral part "4" indicates four DoFs allowed in both + and – directions, while the fractional part "0.2" indicates two DoFs allowed in only one direction. In other words, each partially constrained DoF adds 0.1 UCDoF.

There are three arguments for the above proposal of UCDoF.

1. UCDoF does not adopt the classic DoF definition of independent variables for describing an object's position or movement in a range. Instead, it emphasizes the allowed movements only at the position designated by the fixture. This is because the functioning of fixture often has a strong focus at a fixed position, rather than in a working space.
2. An advantage of adopting allowed movements in UCDoF is the easiness to teach and understand for design practitioners. The concepts of variables and their independence are more abstract than counting the number of allowed movements visually.
3. The proposal for adopting fraction in UCDoF is intended to provide information of partially constrained DoFs. Each partially constrained DoF seems to offer half DoF. However, the author proposes adding 0.1 instead of 0.5 to UCDoF, because two partially constrained DoFs will result in an integer 1, which will cause confusion to the total count of DoFs.

2.2. Freedom-Access-Load-Constraint Model

To effectively conduct fixture design process, for instance how the fixture manages a workpiece during the entry, holding, and exit phases, the prescriptive model of Freedom-Access-Load-Constraint (FALC) is introduced. The total 12 movements are denoted as a set M, which has different subsets for Freedom, Access Loads, and Constraints. In principle, any movement in M shall be either Constraints M_C or Freedoms M_F. Their complementary relation can be expressed below.

$$M_C \cup M_F = M \quad (1)$$

An example of a piercing fixture and tool is shown in Fig. 3. It illustrates the workpiece with a square and cupped shape, shown in blue color. The piecing operation requires that the cylindrical die presses down and leaves a hole in the workpiece.

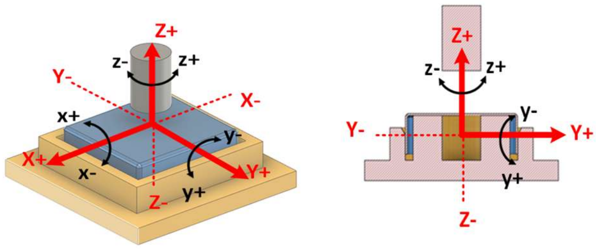

Fig. 3. The coordinate system of a piercing fixture and tool.

A 2-step design process, focusing on the logical relationship among the four subsets, is introduced regarding the example.

- Step1. List all the loads, including forces and moments, among the 12 movements of M. M_L shall be counteracted by geometries or mechanisms such as points, lines, surfaces, friction, and suction. In terms of set, M_L shall be a subset of Constraints M_C.

$$M_L \in M_C \quad (2)$$

Referring to the example, the load is identified in Z-direction as the die presses downwards, hence M_L must be a subset of the constraint M_C. Besides, Constraints M_C also offers positioning the workpiece with the square-shaped wall around, hence includes M_C include 11 movements, as listed in Table 2.

- Step 2. Clarify the Access M_A to the fixture, which indicates the movement(s) of entry and exit by the fixture. M_A must utilize the unconstrained movements, i.e. Freedoms M_F. M_A is a subset of M_F.

$$M_A \in M_F \quad (3)$$

In the example, Z+ is the only unconstrained movement possible for the access M_A. It means the workpiece will enter and exit the fixture by Z+ movement.

Table 2. The LCFA table for the piercing fixture

Move. M	X +	X -	Y +	Y -	Z +	Z -	x +	x -	y +	y -	z +	z -
Load M_L						*						
Cons. M_C	*	*	*	*		*	*	*	*	*	*	*
Free. M_F					*							
Acce. M_A					*							

3. Implementation in Teaching and Student Projects

The kinematic model and design process introduced in Section 2 were taught during a 5-day robot integration workshop in September 2024 to the Professional Bachelor program of Product Development and Integrative Technology at KEA- Copenhagen School of Design and Technology.

The participants were 24 third-year undergraduate students divided into 6 groups, who had commanded basic knowledge and skills in computer aided design, materials, and prototyping. The participants had no prerequisites in robotics and programming.

The task was to integrate the manipulator UR5e produced by Universal Robot into the assembly of medical syringes. Beside the design of gripping tools, each group needed to design a workstation that includes the procedures below.

- Fetching the piston and the pipe from their separate storages.
- Pushing the piston into the pipe.
- Deliver the assembly to the output.

On Day 5, each group demonstrated their solution with both physical workstation and a presentation. Fig. 4 and Fig. 5 are borrowed from the two groups' presentations out of the six. By examining all the 6 presentations, all the 6 groups demonstrated use of FALC table, while one group enclosed the UCDoF model, shown in Fig. 5.

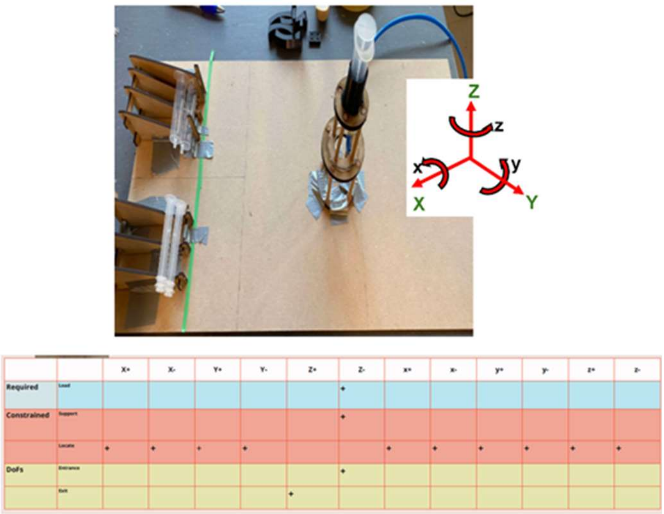

Fig. 4. The workstation and FALC model by one of the student groups.

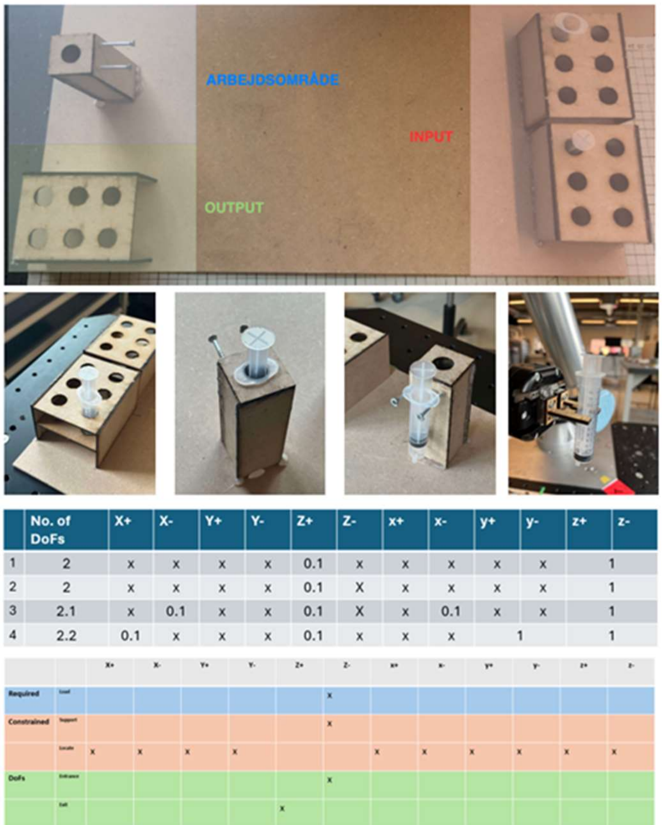

Fig. 5. The workstation, UCDoF model and FALC model by another student group.

The workshop was an attempt at implementing the proposed UCDoF and FALC models in practice. The results demonstrate their adoptabilities, while the latter shows more applicability as a supportive tool in practical development.

4. Limitations and Future Work

This paper gives an overview of the author's efforts in developing a framework for robot fixture design. Beside the proposals, the author admits limitations in three aspects below.

1. The proposed UCDoF and FALC models need more comprehensive validation on a wide range of fixtures. Up to now, the author has only used Cartesian coordinate system, while more complex contact situations, especially with curvatures, for example in [2], are not discussed.
2. The author has not discussed situations with clamps or suctions on the fixtures. When open/close states are involved in UCDoF and FALC models, the design process is expected to be complex.
3. The author has not considered supporting, locating, and clamping as separate functions of fixture, while they are all categorized in constraints. Their differentiation may result in improved quality to the fixture design solutions.

5. Conclusion

This paper proposes mainly two models to effectively facilitate development of robot fixtures. The UCDoF model introduces an informative expression of describing a fixture's constraints to the workpiece. The FALC model is a supportive tool for determining which movement must be constrained or released. The author has attempted to use the models in teaching and development and wish to witness its applications and improvements in boarder academia and industry.

Acknowledgements

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