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**Reconfigurable Modules for Automatic Creating Robotic Courses**

Ana Djuric

Wayne State University, Detroit, MI

ana.djuric2@wayne.edu

Vukica Jovanovic

Old Dominion University, Norfolk, VA

v2jovano@odu.edu

**Abstract**

The main objective of this paper is to describe a teaching tool that can be used for automated creation of different problems that can be used for assessing student knowledge while teaching industrial robotics courses. These materials can be used for instructors who need to create customized questions and answers for different student homework. Wayne State University, Detroit, MI offer different industrial robotics and courses related to fundamental robotic theory: kinematics, dynamics, and control. Old Dominion University, Norfolk, VA offers the course in Introduction to Industrial Robotics. Both programs are Mechanical Engineering Technology under the Engineering Technology departments / division. Preparing questions for assignments, labs and projects can take enormous amount of time because of the equation’s complexity. In order to avoid repetition of same questions especially project problems, the reconfigurable kinematic and dynamic modules are used. This is especially important due to the problems that many instructors are facing due to the online systems that encourage student subscriptions and possible cheating through previously given homework and available solutions from previous exams. The developed model that will be presented in this paper is a reconfigurable module for automatic Jacobian generation that has been developed and validated at Mid-sized University A. Maple tool is used for symbolic equations and clear visibility of results. The methodology is presented in detail. Several examples are used to demonstrate the model’s capability and reusability. The reconfigurable modules are currently used for two robotic curses: Course A and Course B. It will also be expanded to University B and validated there.

**Introduction**

Various industrial robot training software are often very expensive for many schools that offer training these kinds of courses (Kuhl, 2016). Some researchers focused on development on virtual teach pendant for teaching robotics to supplement mathematical approach to teaching all the necessary kinematics that is needed for problems that are defining all necessary conversions that will help engineers to determine required trajectory (Hsieh, 2019). Undergraduate and graduate courses in industrial robotics need to include hands on activities utilizing industrial robots or providing training on robotic simulation software and some researchers developed some robotic simulation tools that can be integrated into courses in other universities (Sergeyev, 2017). At the same time, mathematical problems that explain robot kinematic need to always be recreated and adjusted for each semester that professors are teaching these classes. Instructors have to spend a great deal of time working on the new problems and there is a big chance of errors due to the complexity of equations that are explaining typical 6 degree of freedom industrial robots and different robotic configurations.

Jacobian method has been used for a long time to perform different calculations related to the N-degree-of freedom manipulator with the applications of matrix-vector operations based on the trigonometric functions and their mutual relations in Cartesian coordinate system (Cheah, 2003, Corke, 1996, Denavit, 1955, Orin 1984). This method applies symbolic notation that describe all necessary kinematic properties and break them up in the lower-pair mechanics by means of equations (Denavit, 1955). usual Jacobian matrix is usually derived from input and output velocities equations but might not provide a current estimate for all positioning errors of the platform and possible singularities that might happen during the robot use (Merlet, 2006). Although Jacobian matrix can give the very good prediction of the robotic parameters needed as a starting point for accurate robot control, these physical parameters would have to be adjusted once the program is applied in real time, depending on the robot’s interaction with objects of uncertain lengths, orientations, or gripping points so some other methods are developed to account to the robot dynamics (Cheah, 2003). These applied kinematics models are needed to solve an inverse kinematics problem to generate a desired position in joint space (Cheah, 2003).

**Creating Reconfigurable Model**

A devotement of the n-DOF Reconfigurable Kinematic Model (n-RKM) is highly needed for supporting any kinematic configuration presented in Figure 1, and possible redundant kinematic structures which is intended to support more then 6-DOF.



Figure 1. Process of Unification of reconfigurable Models(Djuric, 2010).

For the 2-RKM the D-H parameters (Denavit, 1955), are presented in Table 1. The twist angle has only five different values, which keeps perpendicularity between joints coordinate frames. Graphical representation of the 2-RKM is shown in Figure 2.



Figure 2. Graphical representation of the 2-RKM (Djuric, 2010).

Table1. D-H parameters for 2-RKM

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***i*** |  |  |  |  |
| 1 |  |  |  |  |
| 2 |  |  |  |  |

All D-H parameters presented in Table 1, are not fixed values. They represent and satisfy properties of all possible machines’ kinematic structures. This is expressed in equations (1)-(4).

Rotational Joints: and (**1**)

Translational Joints: and (**2**)

 (**3**)

 (**4**)

 and are used to control the selection of joint type (rotational or translational), while and are controlling positive joints directions. There values are defined with sin and of a twist angles . Angle has to following values . The mathematical representation of the n-RKM model given in Table 1, can be graphically presented using the Cartesian coordinate system and D-H rules.

**Calculating Reconfigurable Jacobian**

The Jacobian matrix is a linear transformation matrix that maps an n-dimensional joint velocity vector into an m-dimensional end-effector velocity vector. It represents relationship between joint space velocity and task space velocity. When the joints of a robot are actuated, the end-effector moves in its workspace. The location vector of the end-effector is vector with three positions coordinates and three orientations , so:

 (**5**)

The generalized velocity vector is called the twist vector of the end-effector and is formed of linear velocity and angular velocity .

 (**6**)

The recursive Newton-Euler (RNE) method requires velocity vectors computation. The angular and linear velocities for joint can be calculated using the following procedure.

**STEP1:** The joint coordinate frames are assigned using the D-H notation and are expressed with their homogeneous transformation matrices:

 (**7**)

 (**8**)

 (**9**)

**STEP 2:** Separation of 3X3 rotational matrices:

 (**10**)

 (**11**)

 (**12**)

**STEP 3:** Find the transpose of all rotational matrices:

 (**13**)

 (**14**)

 (**15**)

**STEP 4:** Separation of 3X1 position vectors:

 (**16**)

, (**17**)

**STEP 5:** Determine the angular/linear velocities for all joints:

, for rotational joints (**18**)

, for translational joints (**19**)

**STEP 6:** Determine the angular velocities for rotational/translational joints:

, for rotational joints (**20**)

, for translational joints (**21**)

**STEP 7:** Determine the linear velocity for rotational/translational joints:

, for rotational joints (**22**)

, for translational joints (**23**)

 (**24**)

For 2-RKM the Jacobian matrix has been calculated:

 (**25**)

Four type of 2-DOF kinematic structures are evaluated. See Table 2. Each type is defined with two reconfigurable parameters expressed in equations (1) and (2).

Table 2. Four type of 2-DOF kinematic structures

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| TYPE |  |  |  |  |
| RR | 1 | 1 | 0 | 0 |
| RT | 1 | 0 | 1 | 0 |
| TR | 0 | 1 | 1 | 0 |
| TT | 0 | 0 | 1 | 1 |

Each of 2-DOF kinematic structures (RR, RT, TR, and TT) 16 different combinations are created based on twist angles combinations. This reconfigurable platform base on one program will generate 64 different problems and automatic solutions.

Table 3. Reconfigurable parameters and determined by twist angles

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |
| 1 |  |  | 0 | 1 | 0 | 1 |
| 2 |  |  | 0 | 1 | 1 | 0 |
| 3 |  |  | 0 | 1 | -1 | 0 |
| 4 |  |  | 0 | 1 | 0 | -1 |
| 5 |  |  | 1 | 0 | 0 | 1 |
| 6 |  |  | 1 | 0 | 1 | 0 |
| 7 |  |  | 1 | 0 | -1 | 0 |
| 8 |  |  | 1 | 0 | 0 | -1 |
| 9 |  |  | -1 | 0 | 0 | 1 |
| 10 |  |  | -1 | 0 | 1 | 0 |
| 11 |  |  | -1 | 0 | -1 | 0 |
| 12 |  |  | -1 | 0 | 0 | -1 |
| 13 |  |  | 0 | -1 | 0 | 1 |
| 14 |  |  | 0 | -1 | 1 | 0 |
| 15 |  |  | 0 | -1 | -1 | 0 |
| 16 |  |  | 0 | -1 | 0 | -1 |

**Integration of Modules in Robotic Courses**

# The courses descriptions and reconfigurable modules are described in Table 8.

Table 8. Module integration in Robotic Courses

|  |  |  |
| --- | --- | --- |
| ***Courses*** | ***Corse Short Description*** | ***Reconfigurable Modules*** |
| **Industrial Robots Modeling and Simulation MIT 5700***Graduate level* | The direct kinematic problem (homogeneous transformation matrices, links, joints and their parameters, the Denavit - Hartenberg representation, kinematic equations for manipulators). The inverse kinematic problem (geometric and numerical methods for 2-6 DOF).  | Direct kinematic* Inverse kinematic
* Differential kinematics (velocity)
* Jacobian matrix
 |
| **Industrial Robots Dynamics and Control E T 7800***Graduate and undergraduate level* | The direct and inverse dynamic problem for industrial robots. Newton-Euler equations of robot arm motion. A new automatic separation method (ASM) for automatic generation of dynamic equations. Robot trajectory generation. Control of Robot Manipulators (PID control, design of control systems in State-Space and computed torque technique).  | * Differential kinematics (velocity)
* Jacobian matrix
* Forward dynamics
* Backward dynamics
* Automatic separation method
 |
| **Introduction to Industrial Robotics MET 415***Undergraduate level* | The direct and inverse dynamic problem for industrial robots. Newton-Euler equations of robot arm motion. | Direct kinematic* Inverse kinematic
* Jacobian matrix
 |

# These reconfigurable modules are used for creating and solving question in robot kinematics and dynamics. Engineering Technology division at Wayne State University, Detroit, MI, a university that offers MS in robotics program. Two key courses are Industrial Robots Modeling and Simulation ABC (Blind Review) 5700 and Industrial Robots Dynamics and Control ABC (Blind Review) 7800. Introduction to Robotics course is offered at Department of Engineering Technology at Old Dominion University, Norfolk, VA.

**Examples of Problems Created with the Reconfigurable Modules Tool**

Following are given couple examples created with this tool. The first problem has several single 2 DOF are calculated and available in literature (Djuric, 2011, Djuric, 2012a, 2012b, Djuric, 2019, Fu, 1987, Ju, 2020, Orin, 1984) D-H parameters for 2 DOF – RR are presented in Table 4 and the kinematic structure diagram is shown in Figure 3.



Figure 3. 2 DOF – RR kinematic structure diagram.

Table 4. D-H parameters for 2DOF – RR kinematic structure

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Link*** |  |  |  |  |  |  | ***Joint Types*** |  |  |
| 1 |  |  |  |  |  |  | R |  |  |
| 2 |  |  |  |  |  |  | R |  |  |

D-H parameters for 2 DOF–RT are presented in Table 5 and the kinematic structure diagram is shown in Figure 4.



Figure. 4. 2 DOF – RR kinematic structure diagram.

Table 5. D-H parameters for 2DOF – RT kinematic structure

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Link*** |  |  |  |  |  |  | ***Joint Types*** |  |  |
| 1 |  |  |  |  |  |  | R |  |  |
| 2 |  |  |  |  |  |  | T |  |  |

**Validation**

Validation of this model is done by the 2 DOF RR kinematic structure (two degrees of freedom, two rotational joints) has been used for reconfigurable module validation and one 2 DOF RT kinematic structure (two degrees of freedom, one rotational joint and one translational joint). The validated equations are given in the Table 6.

Table 6. Model validation using 2DOF – RR kinematic structure

|  |  |  |  |
| --- | --- | --- | --- |
|  | ***Manual Calculation*** | ***Results Using Reconfigurable Solver*** | ***Jacobian Matrix*** |
| ***Linear Velocity*** |  |  |  |
| ***Angular Velocity*** | **=** |  |

Validation of problem is provided in the Table 7. It was confirmed that presented kinematic structure was done properly and that this model can be used for one of the 64 different problems that are provided with this educational tool. Equations are written using Maple software tools and many configurations are validated while only one example is presented in this paper.

Table 7. Model validation using 2DOF – RT kinematic structure

|  |  |  |  |
| --- | --- | --- | --- |
|  | ***Manual Calculation*** | ***Results Using*** ***Reconfigurable Solver*** | ***Jacobian Matrix*** |
| ***Linear velocity*** |  |  |  |
| ***Angular velocity*** |  |  |

**Conclusion**

A reconfigurable teaching tool for automated creation of different robotics theory problems has been integrated in several industrial robotic courses. This tool is set of parametric equations which includes all possible two degrees of freedom kinematic structures based on Denavit-Hartenberg parameters. This methodology can be recreated in any symbolic based mathematical software such as Maple, MATLAB symbolic box. The reconfigurable modules allow instructors to create more different problems and solutions for students to practice trough labs, assignments, projects, and exams. It is very easy to create additional questions and prepare excellent review material. The main objective of this tool was to assist faculty who are teaching industrial robotics courses in generation of new problems that can be used for homework and exams. Most of the industrial robots have 6 degrees of freedom so these 16 different combinations and 64 different problems are usually sufficient for undergraduate students to learn about industrial robotics.

# **Nomenclature**

- Homogeneous matrices

- Link offset along previous z to the common normal

- Joint angle about z, from old x to new x

- Link length of the common normal

- Twist angle about common normal, for old z axis to new z axis

- Joints types control parameters

- Joints types control parameters

- Twist angles sinus control parameter

- Twist angles cosines control parameter

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**Biographies**

**ANA M. DJURIC** is an associate professor of engineering technology at Wayne State University Detroit, Michigan. Dr. Djuric received her Ph.D. in mechanical engineering from the University of Windsor, Canada. She also holds an M.A.Sc. in industrial and manufacturing systems engineering from the University of Windsor, and dipl.ing in mechanical engineering from the University of Belgrade, Serbia. She teaches various undergraduate and graduate courses in mechanical engineering technology. Her research area is in industrial robotics. Dr. Djuric may be reached at ana.djuric2@wayne.edu.

**VUKICA M. JOVANOVIĆ**, is Chair, Batten Endowed Professor, and associate professor of engineering technology at Old Dominion University, Norfolk, VA. She received her dipl.ing-master and MSc in industrial engineering from the University of Novi Sad, Serbia. She received her Ph.D. in technology at Purdue University, West Lafayette, Indiana, while working as a Ph.D. student in the Center for Advanced Manufacturing. She teaches courses in mechatronics and digital thread. Her research interests include mechatronics, digital manufacturing, manufacturing systems, and engineering education. Dr. Jovanovic may be reached at v2jovano@odu.edu