Modeling and Control of a Articulated Robot Arm with Embedded Joint Actuators

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Abstract— Nowadays human-cooperative robot (HCR) become to be used in the industry and cost-effective manufacturing of it is required. The UR5 robot uses only three type of common-structured rotating joint actuators, which differs from size and power. So this robot become famous cost-effective HCR. The embedded rotating joint actuator for UR5-type HCR is known as a "smart actuator", because only connection of them with links becomes a 6-DOF robot manipulator. Recent development of networked motor drive technology with EtherCAT communication makes this connection and operation of robot manipulator easy. The analysis about forward and inverse kinematics for UR5 is found in many literatures. With help of these materials, the dynamic simulation about a smart actuator for UR5 robot is done in this paper. The co-simulation of motor drive and manipulator dynamics is done with Matlab / Simulink and Simscape Multibody. The results shows that the developed smart actuator is good to substitute the joint actuator of UR5 robot. .

Keywords—rotating joint actuator; smart actuator; articulated robot arm; simscape multi-body, UR5 robot

I. INTRODUCTION

Recently, a lot of human-cooperative robot (HCR) manipulators are developed and commercialized. These robot manipulators requires "light-weight and slim configurations. UR5 robot from the Universal Robotics is a well-known HCR. In robot industry, manufacturing cost of manipulator becomes more important. So modular design and manufacturing schemes are arise. A rotating joint actuator module which controls a link with embedded controller is the basic idea of smart actuator. Series interconnection of 6 independent module can make up a 6-DOF robot manipulator. This means 6 independent 'smart actuator' are basic module for 6-DOF articulated robot. A smart actuator is developed in Korea, which uses EtherCAT communication protocol. The design of electric motor and control algorithm verification of smart actuator is the main purpose of this paper. For this purpose, a brief introduction about UR5-type HCR manipulator is including kinematics, inverse kinematics and modeling is presented. The design of electric motor and its parameters are shown in chapter III. The DH representative joint-link modules are developed in Simscape Multibody model, which is the mechanical parts of the smart actuator. The position controlled permanent magnet synchronous motor (PMSM) servo drive algorithms are developed in Simulink model. The co-simulation method of them is shown in Chapter IV. And final description about the smart actuator model and future works are shown in chapter V.

II. UR5-TYE ARTICULATED ROBOT ARM

For the development UR5-type articulated robot arm, only 3 rotating embedded joint actuators with different size and power are required. The embedded rotating joint actuator with networked control function is called as a smart actuator [1][2].

A. Schematic and frames assignment for UR5 robot

One of the main characteristics of the UR5 is that last three joints of it do not act as a coincidental wrist, which are different from the traditional Stanford manipulator like Puma robot. Therefore all its six joints contribute to the transformational and rotational movements of its end effector. This characteristic makes the kinematics analysis more complex in comparison with other manipulators with coincidental wrist. But recently analysis about forward and inverse kinematics about UR5 is done and complete set of Matlab models for it is available in [4] ~ [7].

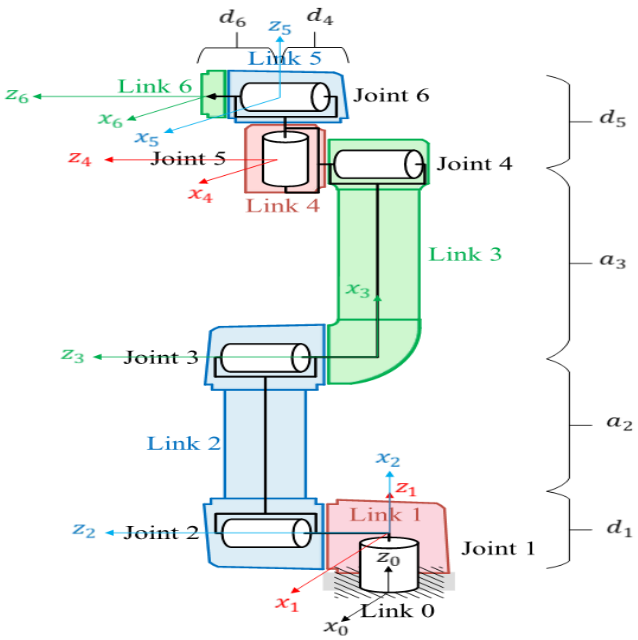

Fig. 1. Schematic and frames assignment of UR5. Redrawn form [4]

B. *Kinematic parameters of UR5 robot*

In the Fig. 1, the schematic of the robotic arm of UR5 and the allocation of each joint's frame are illustrated. The DH parameters of the UR5 for the specified joint frames are presented in the table I, which are given from [4] and [5].

TABLE I. DH PARAMETERS OF UR5

i	a_i (m)	α_i (rad)	d_i (m)	θ_i (rad)
1	0	0	d_1 (0.08916)	θ_1
2	a_2 (0.425)	$\pi/2$	0	θ_2
3	a_3 (0.39225)	0	0	θ_3
4	0	0	d_4 (0.10915)	θ_4
5	0	$\pi/2$	d_5 (0.9456)	θ_5
6	0	$-\pi/2$	d_6 (0.0823)	θ_6

C. *Forward and Inverse Kinematics for UR5 robot*

Using the definition of the transformation matrix of a robotic arm form [3], the transformation matrix from the base to the end effector is in the form of :

$$^{0}\boldsymbol{T}_n = [\,\boldsymbol{n\ o\ a\ p};\ zeros(1,3),\ 1] \tag{1}$$

Then the forward kinematics of the robot position would easily obtained from the fourth column of the $^{0}\boldsymbol{T}_n$ in 1 as:

$$\boldsymbol{p} = [\,p_x\ p_y\ p_z\,]^{\mathrm{T}} \tag{2}$$

For inverse kinematics, we will find the set of joint configurations Q = q_i where $q_i = [\theta_1, \ldots, \theta_6] \in [0, 2\pi)$ such that satisfies (1) which describes the desired position and orientation of the last link. Derivation of the inverse kinematics is presented in [7].

III. DESIGN OF A SMART ACTUATOR FOR HCR

A smart actuator is an embedded joint actuator of robot arm for articulated robot, where 6 rotational joint actuators are used. "SMART actuator" is comprise with motor/ gear/ encoder /amp/ controller/ digital communication board inside the frame of the actuation module [1]. The prototypes of our SMART actuators are also composed of those components. Fig.1 shows the conceptual configuration of our SMART actuators.

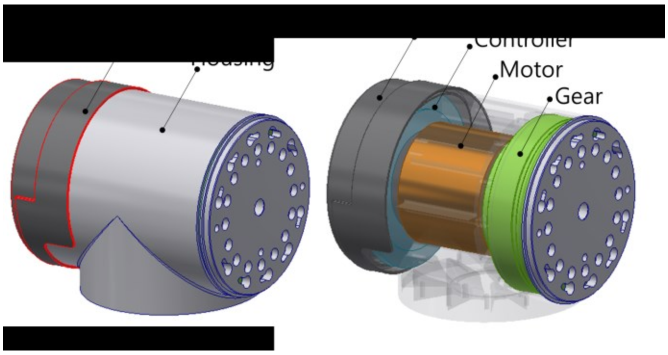

Fig. 2. Configurations of actuator and its main components

A. *Electric motor and gear*

The electric motors, so called 'motors', have been developed depending on required performances for each joint of HCR. In [2] the motor design process is presented for 10kg-payload system. The motors of power 60W, 120W, and 300W have been designed and fabricated for this research in the same way. Fig. 3 shows the configuration of 300W motor as a typical model for base module actuator of UR5. The motor is permanent-magnet (PM) surface-mounted type frameless synchronous motor depending on how classification. Shortly it can be called PM synchronous motor (PMSM). And the attached gear ratio is 101:1.

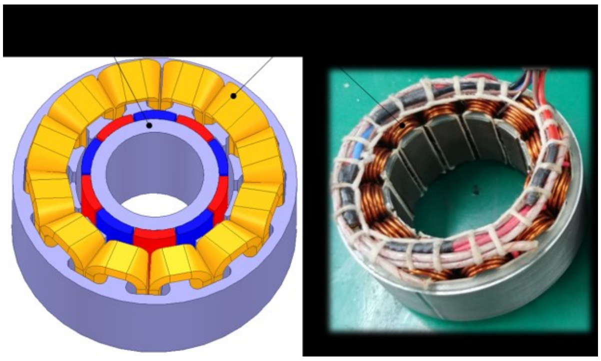

Fig. 3. Frameless motor configuration and its stator picture

B. *Design of electric motor*

PMSM is used for this application because of its advantage such as high efficiency and high torque density. For the 10 pole motor, 12 slots is selected due to lesser in cogging torque than other combinations. The detailed specifications of the designed model for the base module of UR5 are listed in Table I.

TABLE II. MOTOR SPECIFICATIONS

Items	**Unit**	**300W**
Rated output power	W	318.3
Rated torque	Nm	1.52
Rated speed	rpm	2000
Maximum speed	rpm	3000
Torque constant, KT	Nm/A	0.17
Back EMF constant, KE	V/ krpm	14.5
Efficiency	%	91.42
Phase resistance	Ohm	0.105
Phase Inductance	mH	0.585
Rated input current	Arms	9
Stator outer dia.	mm	75.5
Stator stack length	mm	25
Rotor outer diameter	mm	39.5
Weight	kg	0.655

IV. MODELING AND CONTROL OF SMART ACTUATORS

The co-simulation of mechanical manipulator dynamics and electric motor control dynamics of the smart actuator is done in Matlab / Simulink environment. The robot manipulator is implemented in Simscape Multibody model and the control of PMSM is done in Simulink model.

A. Mechanical manipulator model

It is needed to use three basic blocks below for any Simscape Multibody model development. They are Solver, World frame and Mechanism configuration blocks. These blocks define the system's environment (world) and its properties, such as gravity constant and direction. The base of the robot should be defined immediately after the block World frame. For the development of Simscape Multibody model of UR5 robot, DH parameters of table I are considered to provide geometrical specifications. And then assignment of mass, center of mass (COM) and inertia tensor for each part of the robot link and joint are done using UR5 data. In the Simscape Multibody models, the COMs should be expressed in a frame located at the center of geometry (COG) of the body. This is different with the COM obtained by DH parameters, because the COM based on the DH parameters are commonly expressed in the joint frames. So the DH parameters and geometry of the joint is implemented by using only rigid transformation and graphics in Simscape multibody. But for the assign of COMs, transformation of the COMs from the joint frame to the frame located at the CoG of the bodies is done with rigid transformation. After that, mass and inertial tensor is assigned with solid model in the Simscape Multibody model development. After this transformation and using the concept of multi-body system modelling of Simscape Multibody environment, total manipulator model of UR5 robot was developed.

The smart actuator can be expressed as a D-H representative link, because in case of a six-jointed robot with all revolute joints like articulated robot, the 18 numbers of parameters are the form of 6 sets of (ai, ai, di). Finally the robot arm model in Simscape multibody model can be expressed just series connection of smart actuators. The geometry relationship between $(i-1)^{th}$ and i^{th} joints base on the D-H representation can be shown as Fig 5. In the figure, a constant gain of "gear ratio" is used to express the difference between input and output of gear.

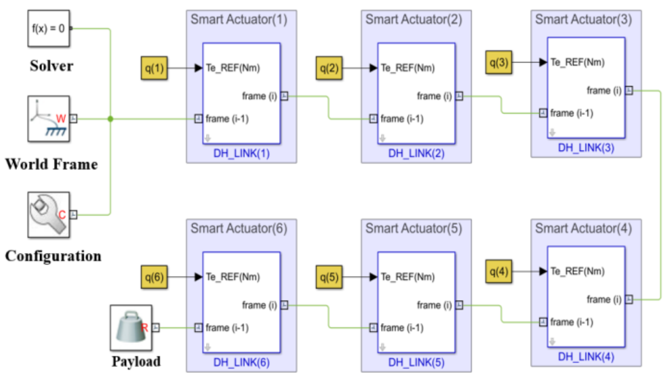

Fig. 4. Simscape multibody model for articulated robot arm

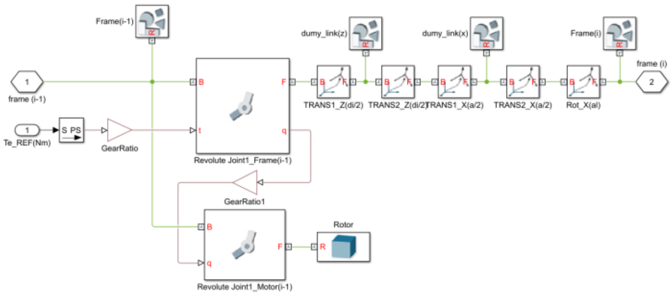

Fig. 5. D-H representation for 1 single link and joint actuator

B. PMSM and its servo control model.

Smart actuator control each joint angle for proper robot manipulation. Driving smart actuator can be thought as position servo-control of PMSM. The overall PMSM control block is shown in Fig. 6. With EtherCAT communications, the smart actuator does as position servo-controller commanded by cyclic synchronous position command

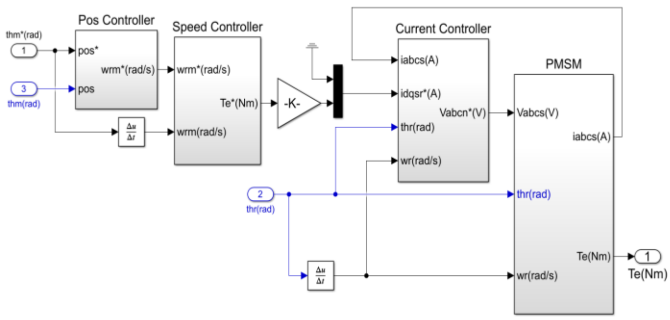

Fig. 6. PMSM and its servo control model

C. Co-slimulation implementation

Fig. 7 shows overall smart actuator model, where the D-H representative link ('DH Link') and servo control system of PMSM is coupled with high-gain gear. In the paper, the overall UR5 robot simulation is done with this model.

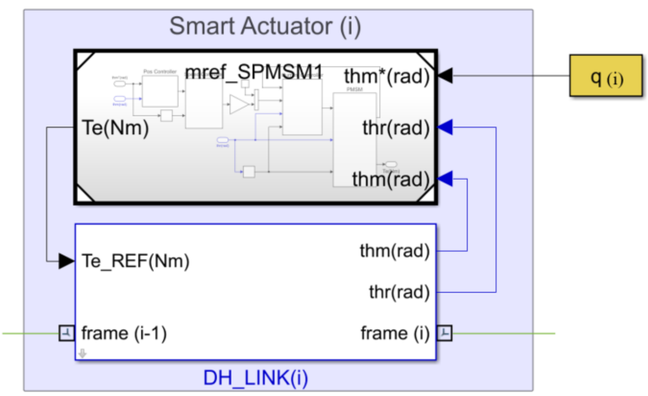

Fig. 7. Smat actuator model combined by D-H link and PMSM servo control

D. Co-simulation results.

The simulation of UR5 robot manipulator is done in Simscape Multibody model with above mentioned controller and plant model. The simulation results and video clips will be shown at the presentation. At this time, the posture of UR5 manipulator acoing to joint angles commands are briefly shown in Fig. 8.

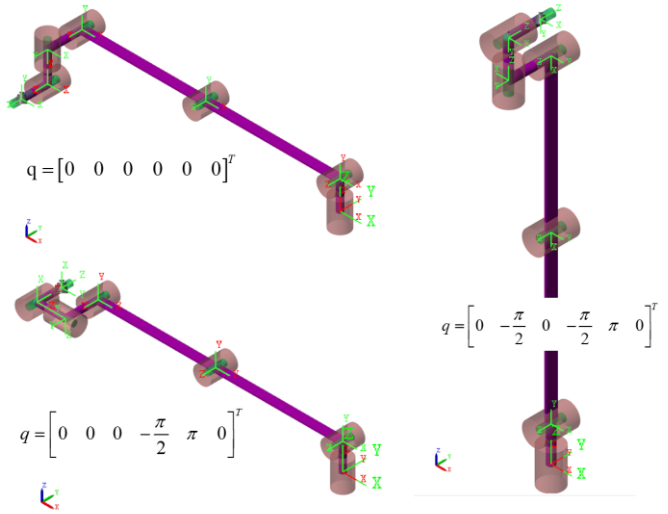

Fig. 8. The posture of UR5 manipulator according to joint angles

V. CONTLUSION

A smart actuator is an embedded joint actuator of robot arm for articulated robot, where 6 rotational joint actuators are used. As an example of articulated robot, the UR5 robot is well-known as a human cooperative robot and its kinematic and dynamic parameters are easily accessible. For the development of smart actuator for UR5 type HCR, draft specification calculation of it is important. Also smart actuator model as an interface for electric motor driven system and mechanical dynamic system. The electric motor driven system is developed in Simulink and the robot manipulator model is done in Simscape Multibody. The overall dynamic performance and visualization of it is down. The next step is implementation of the control algorithms using real time controller like programmable logic controllers with TwinCAT3 software package.

ACKNOWLEDGMENT

This research was supported by Korea Electrotechnology Research Institute (KERI) Primary research program through the National Research Council of Science & Technology (NST) funded by the Ministry of Science and ICT (MSIT) (No. 18-12-N0101-25)

REFERENCES

[1] C. Park, J. H. Kyung, and T.-Y. Choi, “Design of a human-robot cooperative robot manipulator using SMART actuators,” in Proc. Int. Conf. Control, Autom. Syst., Oct. 2011, pp. 1868–1870.

[2] D. Hong, W.Hwang, J. Lee, and B. Woo, “Design, analysis, and experimental validation of a permanent magnet synchronous motor for articulated robot application,” IEEE Trans. On Magnetics, vol.54, no.3, March 2018

[3] J.J. Craig “Introduction to robotics: mechanics and control, volume3”, Pearson/Prentice Hall Upper Saddle River, NJ, USA, 2005

[4] P.M. Kebria, S. Al-Wais, H. Abdi and S. Nahavandi, “Kinematic and Dynamic Modelling of UR5 Manipulator” In Systems, Man, and Cybernetics(SMC), 2016 IEEE International Conference on, pages 4229–4234. IEEE.

[5] R. Keating, “ Analytic inverse kinematics for the universal robots ur-5/ur-10 arms”, Technical report, John Hopkins. 2017. Available at: https://www.slideshare.net/RyanKeating13/ur5-ik

[6] http://rasmusan.blog.aau.dk/files/ur5_kinematics.pdf

[7] K.P. Hawkins, “Analytic inverse kinematics for the universal robots ur-5/ur-10 arms”, Technical report, Georgia Institute of Technology, 2013. Available at: https://smartech.gatech.edu/bitstream/handle/1853/50782/ur_kin_tech_report_1.pdf