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Integrated SolidWorks & Simscape Platform for the Model-Based Control Algorithms of Hydraulic Manipulators

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Abstract: Hydraulic manipulators have been widely used in many different fields due to their high force/torque to inertia ratio. The increased speed of hydraulic manipulators requires solutions to problems ranging from mechanical design to the need to determine a robot model suitable for model-based control. As a solution, this paper presents the integration of SolidWorks with Simscape for designing and controlling hydraulic manipulators. The integration provides a platform for the rapid control prototyping of a hydraulic robot without the need to build actual prototypes. The mechanical drawings of a manipulator are first created using Solidworks and are then imported into Simscape, where the manipulator is represented by connected block diagrams based on the principle of physical modeling. Simulation examples for a 3D manipulator made by KNR SYSTEM INC are verified to show the effectiveness of the presented platform.

Nomenclature

$C(q,\dot{q})$: centripetal-Coriolis matrix
d_i : link offset
$F(\dot{q})$: friction effects vector
$G(q)$: gravity vector
l_i : link length
$p(q)$: end-effector position
$k(q)$: forward kinematic equation
$M(q)$: inertia matrix
$x(t)$: end-effector position and orientation
α_i : link twist
τ : input torque vector
θ_i : joint angle

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1. Introduction

Hydraulic robots have been widely used to manipulate or transport loads in the mining industries, construction, submarine, forestry exploration, and submarine applications as well as in the motion simulators. In spite of the fact that hydraulic actuators have a high force/torque to inertia ratio which can produce very high accelerations, they are rarely used in robots where high speeds are required. In general, the control of hydraulic manipulators is more challenging than that of their electrical counterparts due to not only nonlinear dynamical behavior between control valve input and actuator force output but also the uncertain parameters of hydraulic systems.

As convensional robot control design, it seems that a potentially effective way of increasing the performance of hydraulic robots is to consider model-based control strategies since they take into account modeling uncertainties thereby, enhancing robustness by making the robot track a time-varying reference trajectory [1]. However, the drawback of these approaches is to obtain the dynamic models which can reflect the characteristics of the hydraulic robot exactly. They are essential to analyze the kinematic and dynamics solution, to plan the trajectory of the robot manipulators and to control during the course from their designs to experiment. However, both the kinematic and the dynamics problems of robot manipulators are very complex with difficult computing due to the multi degree of freedom and multi-link space mechanisms of the robot. Furthermore, the fact that hydraulic robots are multi-domain system encompassing hydraulic, mechanical, electrical, and control complicate matters. The effective solution for the development of control strategies of hydraulic robots is simulations, that is, the application of virtual modeling technology adopted by many researchers and scholars nowadays [2,3,4]. It allows the design and development of new control algorithms, mechanical structures of hydraulic robots and helps to define the optimal parameter specifications of a system (control gains, link lengths, masses, etc.). As the complexity of the system under investigation increases the role of modeling/simulation becomes more important.

However, with traditional programming languages, even a simple system is difficult to model [5,6]. First, you need to manually derive the equations of dynamic, and then manipulate them into a form that can be entered into a block diagram representation. Second, it is very difficult to figure out what kind of physical system it is and how the components in this system is practically connected. On the other hand, physical modeling language is also a kind of language but in a totally different way. The object of this work is to research a newly-invented physical modeling language, MATLAB/Simscape [7], and then propose a platform for the development of model-based control algorithms of hydraulic manipulators by integrating SolidWorks & Simscape seamlessly.

2. Modeling

2.1 Geometric 3D Modeling

Fig. 1 indicates a real hydraulic robot and its geometric model which has been built in Solidworks 2012 [8] environment. The hydraulic robot consists of a manipulator and a hydraulic system. The manipulator has 3 links and 3 revolute joints. The 3rd joint is actuated by a crank mechanism. The hydraulic system includes 3 servo valves, 2 hydraulic motors and a hydraulic cylinder which drives the crank of 3rd joint. This assembly model has been built in Solidworks 2012 environment. The Solidworks computes mass, center of mass and inertia of the components automatically. The model is now ready to transfer to the SimScape using Simmechanic Link to be ready for dynamical modeling and simulation.

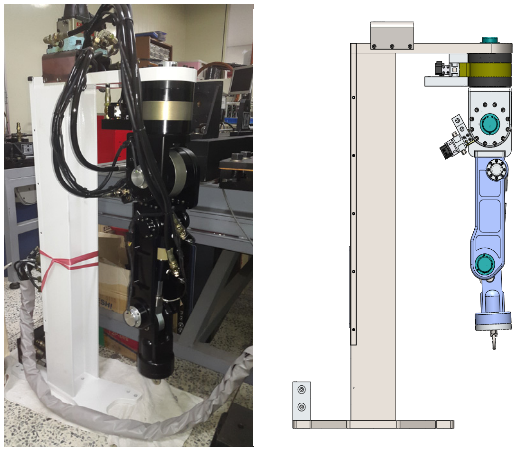

Fig. 1 Hydraulic manipulator and 3D geometric model

2.2 Physical Modeling under SimScape

In one word, when a real physical system is virtually simulated using traditional programming languages, it is not easy to understand what sort of physical system it represents and how the components in this system is actually composed. The invention of physical modeling language puts an end to this embarrassing situation [9]. Physical modeling language is also a kind of language which is used to represent the mathematic model of a physical component – just like traditional programming languages – but in a totally different way. The essential differences can be identified from the following two aspects: there is no assignment-based representation anymore but equation-based representation; and there is no unidirectional signal-based port anymore but bidirectional energy-based port. With equation-based representation, the simulation model can be directly and easily constructed from the corresponding mathematic model; and with bidirectional energy-based port, the behavior of every port and the

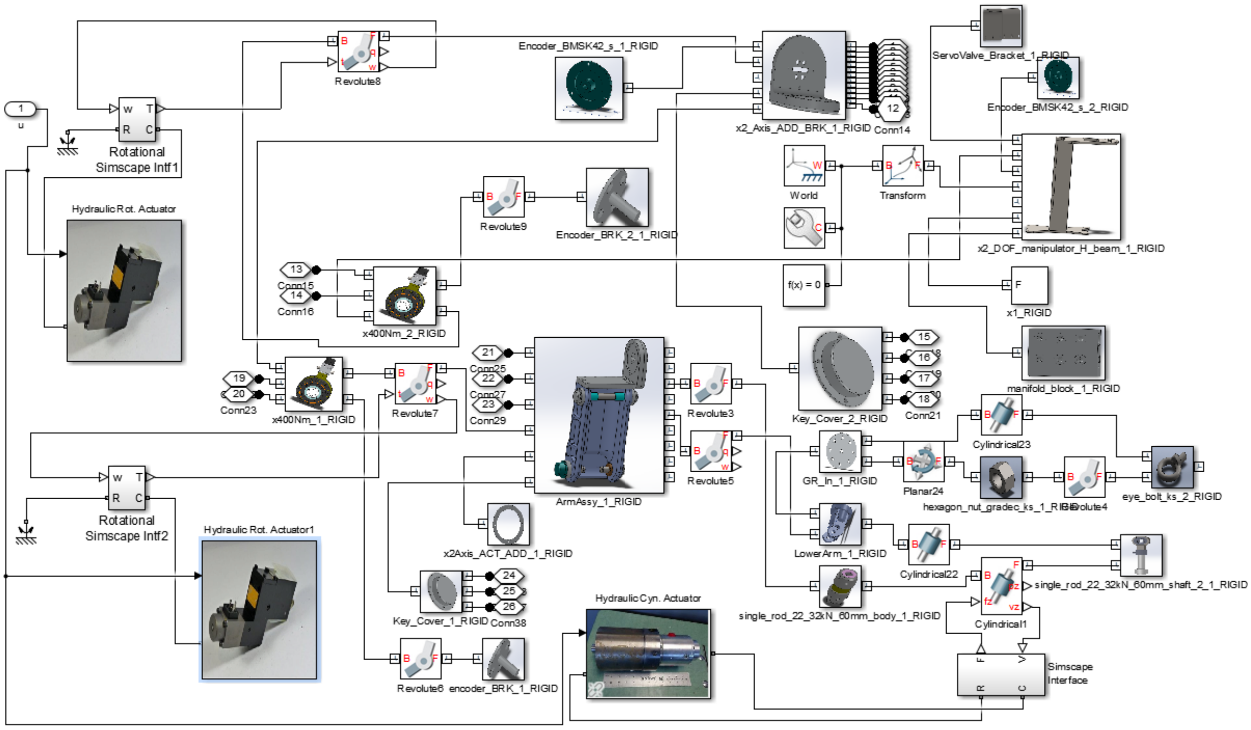

Fig. 2 Physical model of hydraulic robot realized in Simcape environment

connection network of all components will be handled automatically as long as the "energy conservation principle" is determined and then the port on the basis of this principle is described using physical modeling language. Simscape is a toolbox based on multi physics field modeling, which could achieve integrated simulation environment for mechanical, electronic, hydraulic system. It assembles an actual system by building simulation block diagram model, and establishes each module's subsystem in Simscape under Matlab/Simulink, including joints, sensors, hydraulic servo valves, hydraulic actuators, hydromechanical conversion devices, auxiliary hydraulic mechanism, nd related input and output display. The specific realization shows as Fig. 2. Each of blocks shown in pictures symbolizes their own subassemblies which are composed of various components. There are, in addition, Revolute blocks and Cylindrical blocks that denote revolute joints and prismatic joints respectively.

3. Kinematics & Dynamics

3.1 Kinematics

The end-effector position and orientation in the operation space, denoted by $x(t) \in R^m$, is

$$x = k(\theta) = \begin{bmatrix} p(\theta) \\ \phi(\theta) \end{bmatrix} \tag{1}$$

where $k(\theta)$ is the forward kinematic equation, $\theta(t)$ denotes the joint position vector of an n-link manipulator and $p(\theta)$ and $\phi(\theta)$ are the vectors representing the end-effector position and orientation respectively. Table I shows the Denavit-Hartenberg parameters [10] of the hydraulic robot. With this specific parameters, kinematics and inverse kinematics are developed based on coordinate frame system as shown in Fig. 3. Base coordinate frame does not move and is chosen so that it coincides with frame {1} when joint variable θ_1 is zero.

If the end effector is considered to be in position (P_x, P_y, P_z), the kinematic equation for the position of the robot can be computed as Eq. (2)

Table 1 Denavit-Hartenberg parameters

i	Link length(l_i)	Link twist(α_i)	Joint angle(θ_i)	Link offset(d_i)
1	0	π/2	θ_1	-184mm
2	362mm	0	θ_2	0
3	171mm	o	θ_3	0

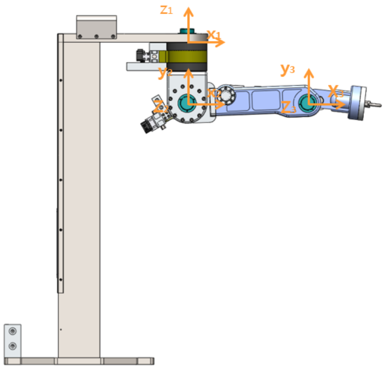

Fig. 3 Coordinate frame system

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} 170.9(C_1C_2C_3 - C_1S_2S_3) + 362.5C_1C_2 \\ 170.9(S_1C_2C_3 - S_1S_2S_3) + 362.5S_1C_2 \\ 170.9(S_2C_3 + C_3S_3) + 362.5S_2 - 184 \end{bmatrix} \tag{2}$$

where C_i, S_i denotes cos and sin of i th joint angle. The joint displacements of the robot can be obtained by using inverse kinematics. This is given by: Firstly, from the geometric view, we obtain θ_1 using the two-argument arctangent function

$$\theta_1 = Atan2(P_y, P_x) \tag{3}$$

Secondly, from the first and second component of Eq. (2), we obtain

$$C_3 = \frac{(P_x/C_1)^2 + P_z^2 - l_1^2 - l_2^2}{2l_1l_2} \tag{4}$$

Assuming the goal position is in the workspace, we write an expression for S_3 as

$$S_3 = \pm\sqrt{1 - C_3^2} \tag{5}$$

Then we compute

$$\theta_3 = Atan2(S_3, C_3) \tag{6}$$

Finally, after some algebraic manipulations we obtain

$$\theta_2 = Atan2(P_z, P_x/C_1) - Atan2(k_2 - k_1) \tag{7}$$

where $k_1 = l_1 + l_2C_3,\ k_2 = l_2S_3$ (8)

3.2 Dynamics

The dynamic model for an n-link robot manipulator is developed in the following form

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + F(\dot{\theta}) = \tau \tag{9}$$

where $M(q), C(q,\dot{q}), G(q), F(\dot{q})$ and τ represent the inertia matrix, the centripetal-Coriolis matrix, the gravity vector, the friction effects vector and input torque vector respectively.

4. Simulations

Models are built, simulated, and tested incrementally. In other words, an idealized, simplified model is adopted at the start. After the model is simulated, verified that it works the way as expected, it then improved more realistic by taking into account effects such as friction loss, motor shaft compliance, hard stops, and the other things that describe real-world phenomena. An actual power unit of our hydraulic system, as shown in Fig. 4, consists of a fixed-displacement pump, reservoir, pressure-relief valve, and a prime mover that drives the hydraulic pump. Depending on particular applications, the model of a power unit can be simplified practically without a loss in accuracy. Assuming that pump delivery exceeds the system's fluid requirements at all times, the pump output pressure

remains practically constant and close to the pressure setting of the pressure-relief valve. If this assumption is true and acceptable, the entire power unit is reduced to an ideal Hydraulic Pressure Source block, as shown in Fig. 5. The key parameters of the hydraulic motor block are the motor displacement, volumetric and total efficiencies, nominal pressure, and angular velocity. The main parameters of servo valve are orifice width, flow discharge coefficient, initial opening, orifice orientation, critical Reynolds number, and leakage area. The values of main parameters in this study are given in Table 2.

Table 2 Values of main hydraulic parameters

Hydralic motor		Servo valve	
Motor disp.	1e-5m^3/deg	Orif. width	0.05 mm
Vol. eff.	0.92	Flow coeff.	0.7
Total eff.	0.8	Init. opening	0
Nom. pres.	100e5 Pa	Rey. no.	12
Ang. vel.	180 rad/s	Leak. area	1e-9 m^2

To illustrate the performance of the proposed integrated platform presented in this work, a set of simulation results are presented in this section. The simulations with various payload and velocity conditions are conducted MATLAB/Simulink environment as shown in Fig. 6 which consists of three parts: the hydraulic robot, controller, trajectory planner. The simulation subject is the virtual model of the hydraulic robot made by KNR SYSTEM INC. in Korea. The controller can perform tasks reliably from PID control to advanced control such as model-based control by means of Simulink toolboxes. The trajectory planner provides reference paths in joint or task space. The manipulator moves from at rest at the joint angles θ = [0 3.6 0] at rest to θ = [1 2.9 1.5] at rest in 10 second by PID control. Fig. 7 shows the desired joint-space trajectories and Fig. 8 is the successive 3D-view of the hydraulic robot. Due to 3D view, the robot movement in manipulation space is easily understandable. The tuned PID gains are given in Table 3.

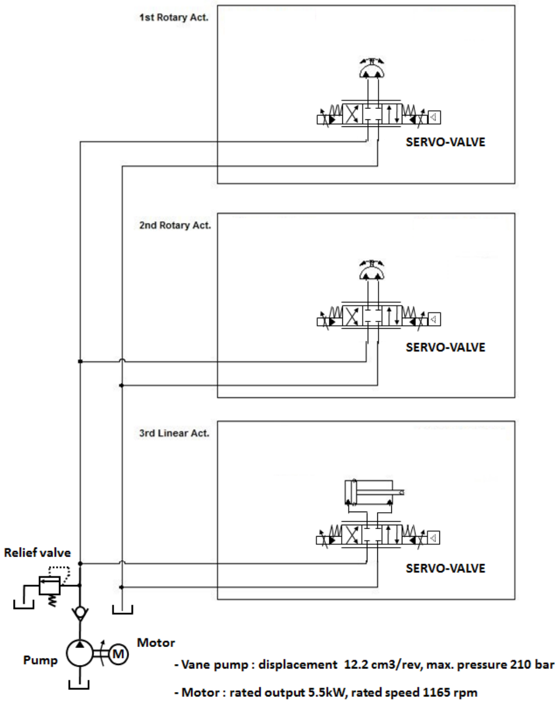

Fig. 4 Hydraulic diagram of hydraulic robot

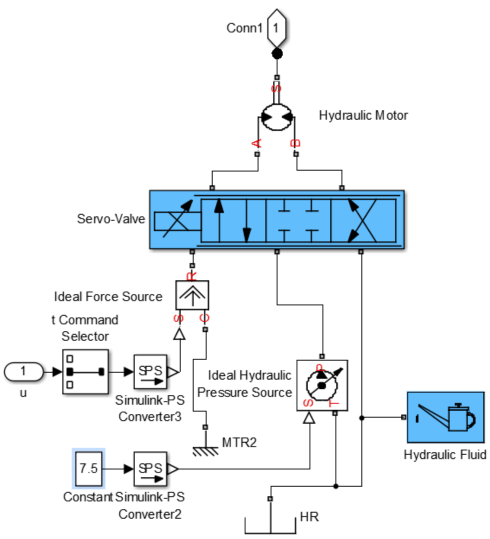

Fig. 5 Simscape model of hydraulic power unit

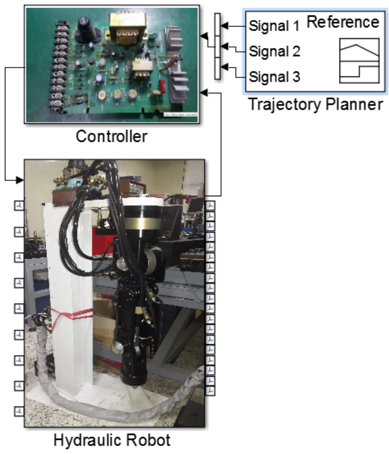

Fig. 6 Whole system architecture of platform

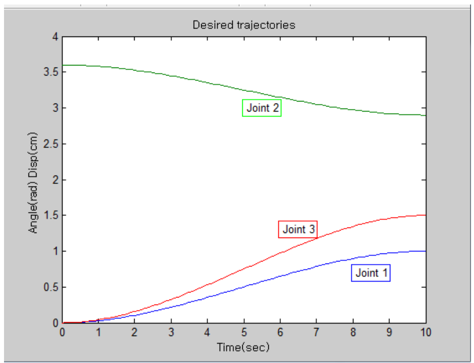

Fig. 7 Desired Trajectories

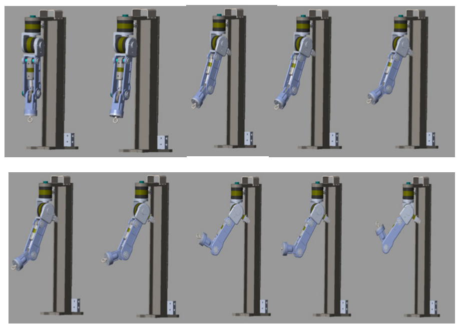

Fig. 8 Sucessive 3D view of movement

Table 3 PID controller gains

Joint	1	2	3
Proportional	10000	10000	120
Integral	100	100	10
Derivative	2	2	2
Filter coeff.	100	100	100

Fig. 9 and 10 show simulation results which can be easily produced with the help of Matlab graphic commands. In order to verify the specific effectiveness of the dynamic modeling and hydraulic system, it is necessary to implement experiments with the real system. Though experiments are not implemented in this study, it is undoubtedly verified that the proposed platform provides the method that enables the efficient development of a controller and system modeling from the beginning stage of the hydraulic robot design.

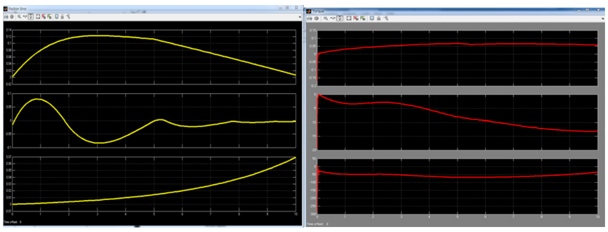

Fig. 9 Simulation plots of error and torque

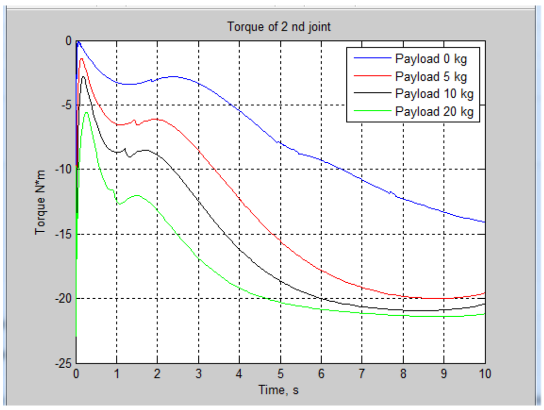

Fig. 10 Torque plots of 2 nd joint

5. Conclusion

The presented platform shows rapid control prototyping of a hydraulic robot without the need for building a real prototype. Simulation examples for 3D manipulator made by KNR SYSTEM INC. are testified to show effectiveness of the presented platform. In this paper the dynamic model for usage with model-based control algorithm of a hydraulic robot is rapidly developed from SolidWorks 3D model seamlessly. In addition, it is possible to integrate the physical model completley in a simulation environment for motion control, verification and optimization. with the aid of Matlab toolboxes. Based on this platform it enables us for further researches in fields like high payload-to-weight, rapid response, and precision applications which require dynamic models of robot manipulators.

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