SYSTEMATIC DESIGN OF A DESKTOP ROBOT ARM IN SOLIDWORKS AND MATLAB SIMULINK

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Abstract:

Robot arms are complex mechatronic systems whose design is a challenging and time-consuming task. Recently, low-cost small-size desktop robot arms have been increasingly used in education, research, households, etc. This paper presents the systematic design of a 6DoF desktop robot arm with cylindrical joints actuated with stepper motors. Within the design, the main goals were to achieve cost-effectiveness of the construction, to enable the simplicity of the control unit, and to achieve fast dynamics and good repeatability. The virtual simulation system of the manipulator, built using the integration of 3D design and modern multibody simulation environment, improves the robot design and the efficiency of the robot control system. 3D modeling of the robot arm is performed in SolidWorks. The location of each motor as well as the selection of the power transmission method achieve a reduction of the required moments in the joints during the robot movement. Verifying of motors' dimensioning is performed using numerical simulation of robot inverse dynamics problem based on the SolidWorks 3D robot model for the desired robot operations within the Simulink environment by using Simscape Multibody.

Key words: desktop robot, design, virtual model, stepper motors, SolidWorks, Simscape Multibody.

1. Introduction

The number of technologies that turn to the employment of industrial robots to facilitate their production process is on a constant increase [1]. Robot arms are used for many industrial applications, such as handling, painting, assembling, welding, etc. [2]. However, industrial robots of renowned manufacturers have significant prices. Recently, there has been a demand on the market for small-size (desktop) and low-cost robots where low-cost implementation prevails over the need for high dynamic performance [3]. Under the background of strategies such as Industry 4.0, Made in China 2025, Advanced Manufacturing Partnership (AMP), Industry 4.1J, etc., more and more vocational schools have been setting up industrial robot majors. As a solution, low-cost desktop robots are proposed for academic and research purposes [4].

Three main components in developing a robot arm system include 1) the mechanical design and structure, 2) an interface device, actuators, and sensors, and 3) a controller [5]. Within the design of desktop robots, designers' goals are oriented to make the robotic system cost-effective, with simple constructions, fast dynamics, and a good repeatability of movements. Considering the practical realization of a robot, significant costs go to applied actuators with transmission systems, a control unit, and custom-machined components. Nowadays, engineers make use of CAD software for design and simulation, where their compatibility with the modern multibody simulation environment for 3D mechanical systems provides a time and cost-effective method of research and development.

In desktop manipulators, stepper motors are frequently used due to the ease of control of their position without feedback. Feedforward control, often chosen as a control strategy for stepper motors due to the simplicity of control algorithms, as well as the cost-effectiveness of the solution, is chosen as a control method in this study. The absence of feedback implies that the conditions (trajectory scope) under which the robot arm operates are strictly defined in order to avoid the occurrence of "step skipping" throughout the robot operation. Selection/dimensioning of actuators have to be carefully performed depending on intended robot applications. Dimensioning of motors additionally plays an important role within the design of the desktop robot mechanical structure [6], as their mass/inertia often make up most of the desktop robot's mass/inertia.

This paper presents the systematic design of a desktop robot arm with six degrees of freedom actuated with stepper motors using available modern software multibody design and simulation tools. The virtual simulation system of the manipulator is built, which improves the robot design and the efficiency of the manipulator control system [7] using Solidworks [8] and Simscape Multibody simulation platform [9]. Modeling of 6Dof desktop robot arm in Solidworks is presented. The design of the transmission system, as one of the most important aspects of robot mechanical design, is described in the paper in detail. 3D assembly from SolidWorks was integrated into Simulink Simscape Multibody via a plug-in, and numerical solution of inverse dynamics problem is simulated in order to verify the motor dimensioning for intended applications.

This paper is divided as follows. In Section 2, the 3D design of the robot arm, including the design of the torque transmission system, is presented. In Section 3, the verification of the dimensioning of the robot based on Simscape Multibody numerical simulation of inverse dynamics is presented. Concluding remarks are given in Section 4.

2. 3D modeling of the robot arm including the design of the torque transmission system

Modern software tools for 3D modeling of machine assemblies ease the problem of constructing machine parts and assemblies but also possess the ability to synchronize with multi-body dynamics simulation software by creating suitable files that can be exported and executed via the plugins. The definition of the kinematic structure of the 6DoF robot arm with cylindrical joints is followed by the design and coupling of the robot links. The constructed desktop robot with six degrees of freedom is shown in Figure 1. The links of the robotic arm are named herein in the following order: shoulder, upper arm, elbow, forearm, hand, and finger [10]. In order to achieve the fastest dynamics of the robot, it is necessary to position the center of mass of the robot be as close as possible to the stationary support (base) to reduce the required motors' moments/forces for the given movement. Guided by this, the motors that drive the joints were placed as close as possible to the stationary support, which allowed the motors to be smaller in mass, dimensions, and cost. The electronics with the microcontroller that controls the motors are also located in the base.

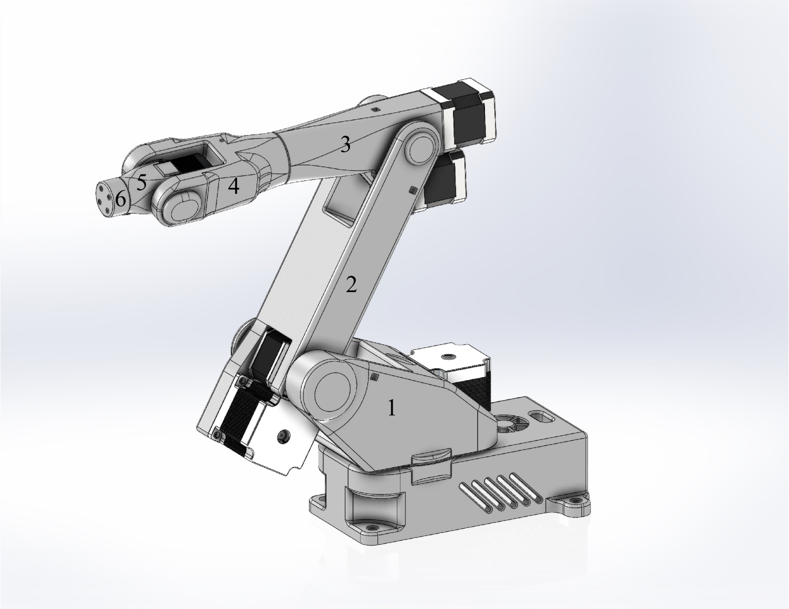


Fig. 1. Designed robot arm with six degrees of freedom. Legend: 1-shoulder, 2-upper arm, 3-elbow, 4-forearm, 5-hand, 6-finger

The design of the transmission system is one of the most important aspects of robot mechanical design. The most well-known transmission systems used in robot manipulators are strain wave gearing (harmonic drives) and toothed belt pulleys [6]. Toothed belts are used herein as a cost-effective solution that enables transmission of power from the stepper motor to the joints so that the motors are as close as possible to the base. Toothed belts are characterized by smaller backlash compared to conventional gears and enable easy change of the transmission ratio by using pulleys of different sizes. The specific design of the transmission system for the constructed desktop robot arm is described in this chapter. In Figure 2, the designed transmission method of the torque from the motor by the belt to the shoulder joint is presented.

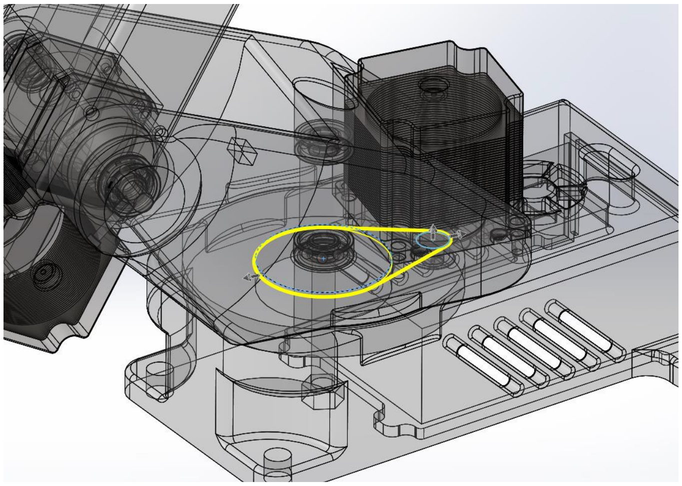


Fig. 2. Transmission of power method of the motor by the belt to the shoulder joint

In Figure 3a, the elbow (link No 3) belt transmission method is depicted. The motor located below the motor that drives the second link (in grey color in Figure 3a) drives the elbow link. In Figure 3.b, the forearm (4th link) joint's belt transmission method from the motor which is attached at the end of the upper arm (2nd) link, is described.

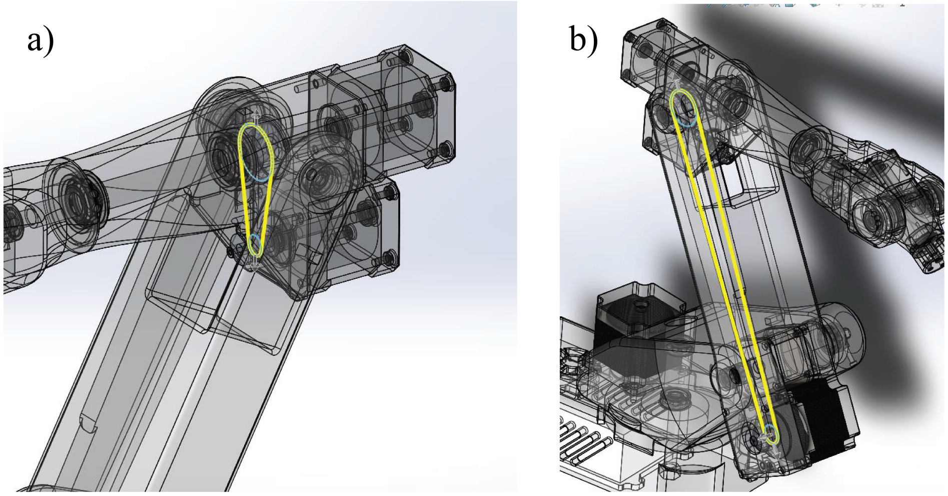


Fig. 3 a) Elbow joint belt transmission method, b) 4. Forearm joint belt transmission method

One of the biggest challenges was placing the motor that drives the hand (5th) link onto the elbow (3rd) link. It was necessary to find a way to couple the motor of the hand link through the elbow and the forearm link to the hand joints. That construction problem was solved in such a way that the forearm rotates about an elbow axis of symmetry, and the shaft of the hand motor is placed along the forearm rotational axis. At the end of the motor shaft, there is a pulley rigidly attached to the motor shaft and coupled by a toothed belt to the hand joint. The rotational axes of the two pulleys are at an angle of 90 degrees. In order to couple those two belts, the belt had to change direction using two additional pulleys, as presented in Figure 4.

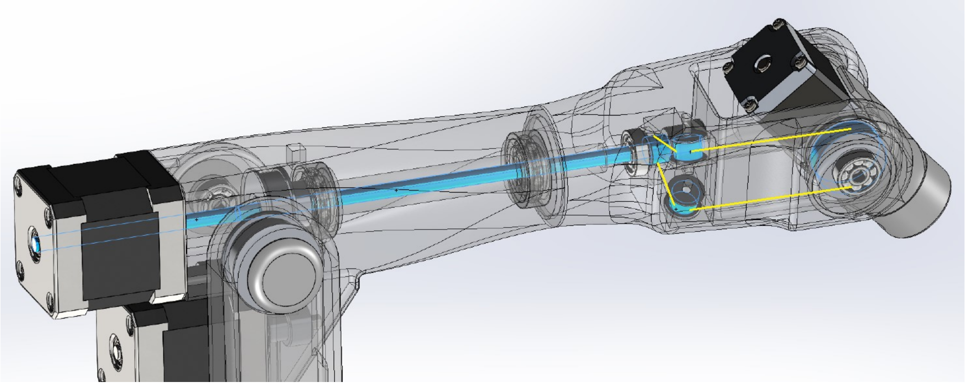


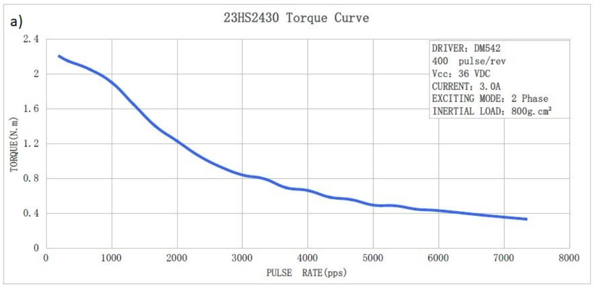
Fig. 4. Hand joint belt transmission method inside forearm link.

Presented low-cost and efficient design of the transmission system enabled placements of the motors as near the base as possible, reducing the required motor torques and sizes.

3. Verification of stepper motors using numerical solution of inverse dynamics problem in Simscape Multibody

Feedforward control of a stepper motor can only achieve successful trajectory tracking under the condition that the required motor torques/forces for the programmed trajectory can be achieved by the installed motors throughout the entire robot operation. Due to the absence of feedback, i.e., the inability to compensate for an error, it is of paramount importance to make sure that the robot motors are dimensioned according to the intended application in order for motors not to "lose" ("skip") steps. For this reason, the possibility of considering the integration of high-degree of precision 3D mechanical model and modern multibody simulation environment is very beneficial for verifying the dimensioning of the applied motors.

The initial selection of stepper motors has been performed herein based on simple static calculation for the robot configuration with the maximum static load in the joints, which is the configuration in which the robot arm is completely horizontally positioned so that the robotic gripper can withstand a vertical force of up to 10N. Based on initial static calculations, stepper motors with torque up to 0.6Nm are initially selected [11]. The motor manufacturer provides a torque/speed curve which is shown in Fig. 5a. By defining the moment-angular velocity plot for every robot joint by the desired robot movement using the numerical simulation of the inverse robot dynamics problem, a simple comparison of the two graphs for each motor can verify the dimensioning of the selected stepper motors.



b)

	Motor	Holding torque
Joint 1	23HS5628	504 Ncm
Joint 2	17HS3401	608 Ncm
Joint 3	23HS5628	236 Ncm
Joint 4	17HS3401	96 Ncm
Joint 5	17HS3401	96 Ncm
Joint 6	11HS3410	60 Ncm

Fig. 5. a) Stepper motor torque-speed curve [11], b) Holding torque of chosen stepper motors with reducers

A robot dynamic model is time variable, highly non-linear, and characterized by coupling effects among the robot joints [12]. The solution of the robot inverse dynamic problem, ie. the calculation of the required robot actuators' torques/forces from a specification of the robot's trajectory can be obtained analytically, or by using ready-made modeler/simulator software solutions based on 3D software robot models. The latter avoids solving complicated mathematical expressions [12].

Matlab supports the installation of additional packages (add-ons), such as Simscape Multibody Link, which is used to import assembly models from CAD applications to Simscape Multibody. Using Simscape Multibody, a 3D model of the robot arm designed in SolidWorks is transformed into a dynamic model in Simulink environment. In SolidWorks, by selecting the Simscape Multibody Link option, a file with the extension .hml is created, which contains all the necessary parameters for creating a dynamic model in Simscape Multibody, such as mass, inertia, a center of mass, etc., for each part of the assembly separately, as well as the type of joints by which they are connected. For the purpose of inverse dynamics simulation, the cylindrical joint function blocks with two ports, an actuator and a sensor port, were used. The input value of the joint bloc, a series of discrete joint positions in radians obtained from the trajectory planner, is brought to the actuator port, while the output of the sensor port is the series of the calculated joint moments for the given input.

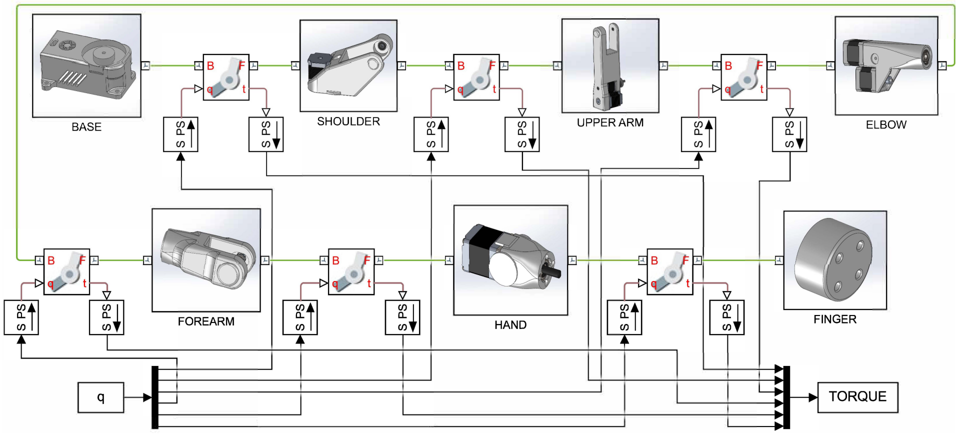


Fig. 6. Simscape Multibody dynamic model of the designed desktop 6DoF robot arm obtained from SolidWorks .hml file

In Fig.7a, a time change of the required moment for the upper arm joint and the desired robot motion obtained by Simscape Multibody simulation model in Fig.6 is given, while the angular velocity for the same joint calculated from the trajectory planer is given in Fig. 7b. The upper arm joint is chosen here since it is the most loaded motor.

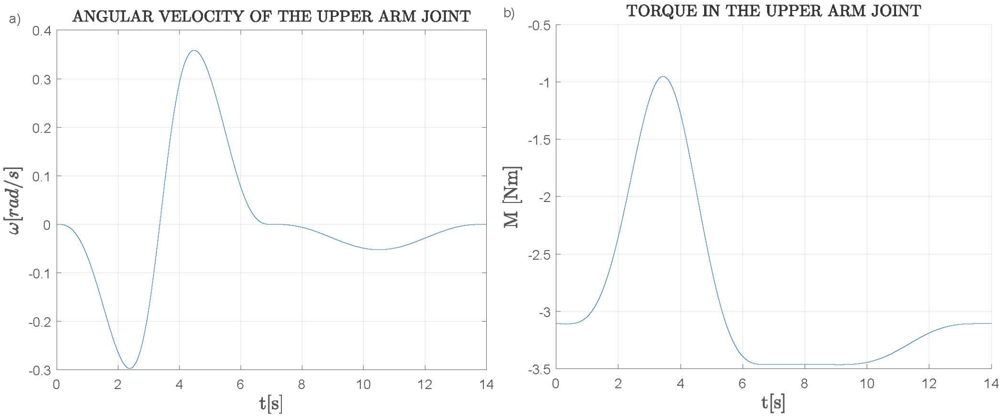


Fig. 7. a) Angular velocity of the upper arm joint calculated in the trajectory planner, b) Torque in the upper arm joint obtained by simulation model in Simscape Multibody.

In Fig. 8.a, the torque/angular velocity plot composed from the time change of the calculated motor's moment and the time change of calculated angular velocity for the desired robot motion and the considered joint is presented. In Fig. 8b, the mentioned torque/angular velocity dependence is presented in absolute coordinates for the simplicity of display and comparisons with the manufacturer's torque/speed curve.

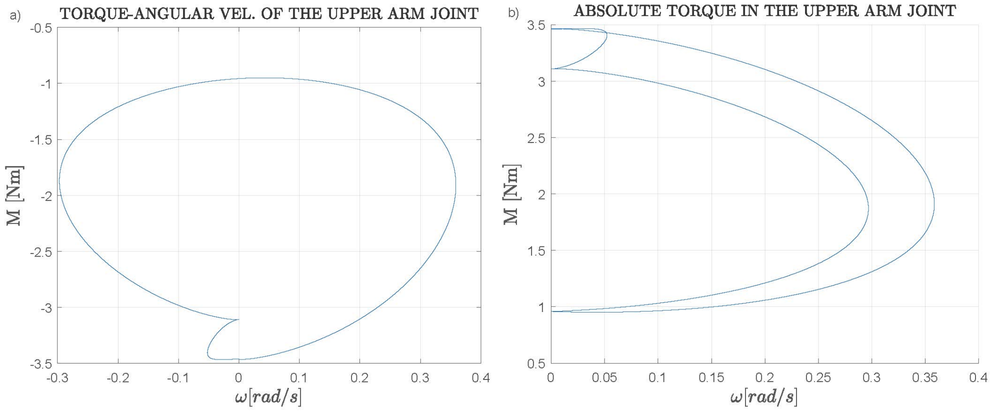


Fig. 8. a) Torque/angular velocity plot for the upper arm joint, b) Absolute torque/angular in the upper arm joint

In Fig. 9. the comparison of the obtained torque/angular velocity plot from Fig 8.b (yellow curve) and the manufacturer's torque/speed curve that presents the maximum moments motors can produce depending on rotor speed without causing the desynchronization of the stepper motor, is presented. The blue curve is the curve obtained from the manufacturer documentation [11], while the red curve is the "scaled" motor torque/speed curve obtained by applying a safety degree of 20% to account for friction and other unmodelled uncertainties of the dynamic model. It has to be noted that the load of mass 1kg was simulated, which corresponds to the maximum load capacity of the constructed robot.

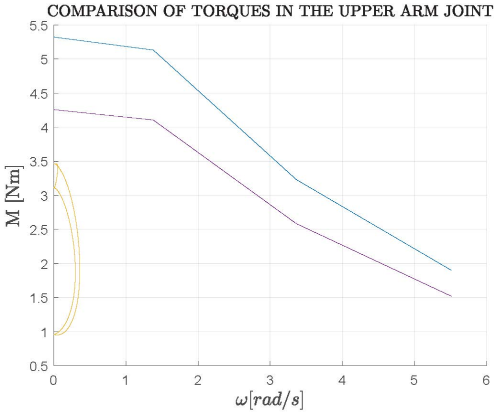


Fig. 9. Comparison of torques/speed curves in the upper arm joint during manipulation.

As can be seen from Fig 9, the obtained torque/angular velocity plot for the selected motor is located below the curve for the entire robot operation, which implies that the desired robot motion will not cause the occurrence of steps skipping. Also, the resulting curve is not excessively smaller compared to the manufacturer's torque/speed curves, from which it can be concluded that the selected motor is not oversized, which is in compliance with the designer guidelines-selecting small motor as possible (which decreases the mass and the price of the construction) for the desired robot applications.

4. Conclusion

In this study, the systematic design of the mechanical structure for the 6DoF desktop robot arm with cylindrical joints actuated with stepper motors based on the usage of available modern software multibody design and simulation tools is presented. The adopted principles and the followed guidelines for designing a low-cost desktop robotic arm are described. Stepper motors are selected for ease of control of their position without feedback motors. The design of the transmission system, as one of the most important aspects of robot mechanical design, is described. The virtual simulation system of the manipulator is built, which improves the robot design, and the efficiency of the manipulator control system using Solidworks and Simscape Multibody simulation platform. Verifying of motors' dimensioning is performed using numerical simulation of robot inverse dynamics problem based on the SolidWorks 3D robot model for the desired robot operations. Application of software tools that simulate a solution of the inverse robot dynamics problem could be especially suitable for quick and simple adaptation of the designed robot's mechanical structure.

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