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Design and Construction of a Linear-Rotary Joint for Robotics Applications

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***Abstract*—In this paper the mechanical design process of a special linear-rotary joint for a SCARA robot, called FUM SCARA, is illustrated. FUM SCARA is constructed in the Robotics Lab of Ferdowsi University of Mashhad, in Iran. Main features of this robot are overall ±0.015 mm repeatability in XYZ plane, 8.5 m/s end-effector velocity and 0.5 seconds full pick and place cycle time. FUM SCARA robot is capable of doing applications such as pick and place and assembly in production lines using a custom designed linear-rotary joint. SCARA is a common industrial robot with inherent high joint repeatability and rigidity. As a result, repeatability of the proposed joint is essential. To pick up and place a work piece, a vacuum system tubing must be designed into the linear-rotary joint. Mechanical design process, includes linear-rotary joint design and selection of the required components. The effectiveness of the presented joint and the robot is investigated through experimental and simulation results.**

Keywords—linear-rotary joint; industrial robot; joint mechanical design

I. INTRODUCTION

Robotic arms have various and widespread applications in modern industry. SCARA robot has a special role in assembly lines with three revolute joints and one prismatic joint [1]. Different manufacturers have industrial robots with a wide range of variety in velocity and repeatability. Although there are different kinds of applications for industrial robots, most of them have an inaccessible control systems. However, there exist some collegiate robots which offer open architecture control systems [2-3].

Robotic power transmission systems have also attracted the attention of many researchers. A new non-linear direct drive train, called gimbal drive, has been illustrated in [4]. The gimbal drive makes it possible to eliminate inertia and mass of motors by locating them in robot base. In [5], authors have optimized a power transmission of a robotic arm in order to reduce the weight of robot links. The effect of using harmonic drives in SCARA robot has been studied in [6]. Additionally, different kinds of adaptive controllers have been studied and applied to a direct drive SCARA robot in [7]. Reference [8] categorized kinematic chains based on the location of linear-rotary actuator in the chain.

This paper presents the mechanical design of a new economical linear-rotary joint. This new joint is applied in the FUM SCARA robot as third and fourth joints (Fig. 1). All needed components for linear-rotary joint are illustrated. A standard cycle time trajectory is used for the SCARA robots [9]. This trajectory is a basic performance criterion for SCARA robots and is used by major robot manufacturers. Standard components are selected so that the robot can complete the trajectory satisfactorily. Repeatability of the proposed joint is calculated based on ISO 9283 [3], [10].

The presented paper is organized as follows: Section II illustrates the FUM SCARA construction goals related to the design of the linear-rotary joint. The mechanical design of the proposed joint is investigated in section III. Cycle time trajectory and FUM SCARA robot's workspace are described in section IV and V, respectively. Experimental results using a PID controller through the cycle time trajectory are presented in section VI. Finally, section VII concludes the paper.

II. GOALS OF FUM SCARA ROBOT DESIGN

The main goal of the FUM SCARA robot construction is to design a robot which its performance can be compared with commercial robots. Open control architecture design of FUM SCARA robot allows users to easily apply new control algorithms. Its high performance and the ability to implement

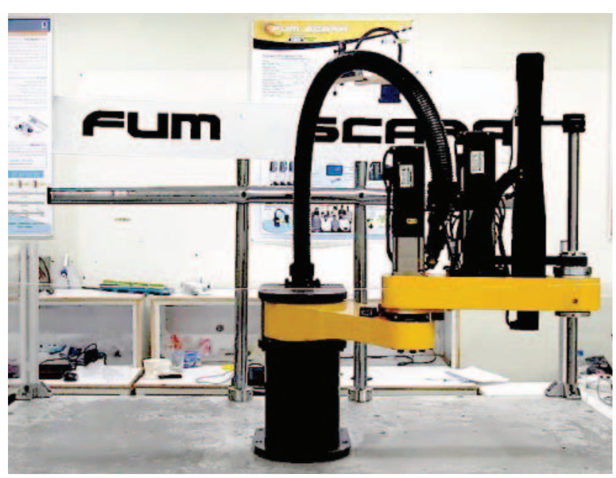


Fig. 1. FUM SCARA robot

new control algorithms make it a unique robot. The installation technique of gearbox in this design is another considerable feature of FUM SCARA. Through this method, there is no bending on the gearbox shaft in all revolute joints.

Design parameters are as follows: payload, workspace and reachability, maximum velocity, repeatability and cost [11]. The FUM SCARA robot is a medium size SCARA robot type which can be used in many applications such as pick and place and high speed assemblies requiring high precision. Specifications of FUM SCARA robot are compared with well-known manufacturers' data in [3].

III. MECHANICAL LINEAR-ROTARY JOINT DESIGN

The main criterion of joint design is the cycle time trajectory with pre-defined velocity and acceleration in addition to repeatability. Power transmission selection of the linear-rotary joint is important due to the effects of the joint weight on other power transmission systems. The lower the weight of the second link leads to less motor torque for the first and the second robot joints. Design algorithm is based on predicting the power transmission system and the estimation of its inertia and mass. Required torque for robot joints can be computed by simulating the cycle time trajectory. Next, considering the computed torque from previous step, the new power transmission system is selected. If the results of the recent design do not correspond with the first one, the design algorithm is restarted from the first step. This procedure will be repeated till the previous and recent power transmission systems match together. The applied algorithm to select the power transmission system is depicted in Fig. 2. This algorithm is completely illustrated in [3].

The algorithm must be applied to rotary part of linear-rotary joint to select suitable planetary gearbox. Linear part of this joint has no gearbox and motor shaft is connected to ball screw directly through a custom coupling. Linear and rotary motion of the end-effector are achieved by ball screw and ball spline, respectively. The selection procedure of the ball screw as the most important part of the joint is depicted in Fig. 3.

Accuracy grade and efficiency of the ball screw are selected based on demands. The standard combination of lead and screw shaft diameter are listed in manufacturers' catalogs [12]. According to application, screw shaft mounting method is chosen. As shown in Fig. 4, there are four common types of

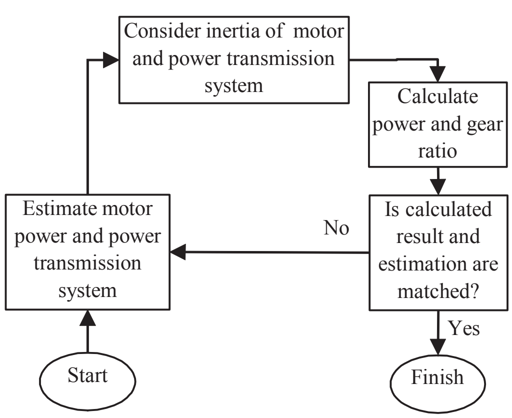


Fig. 2. Motor and planetary gearbox selection flowchart

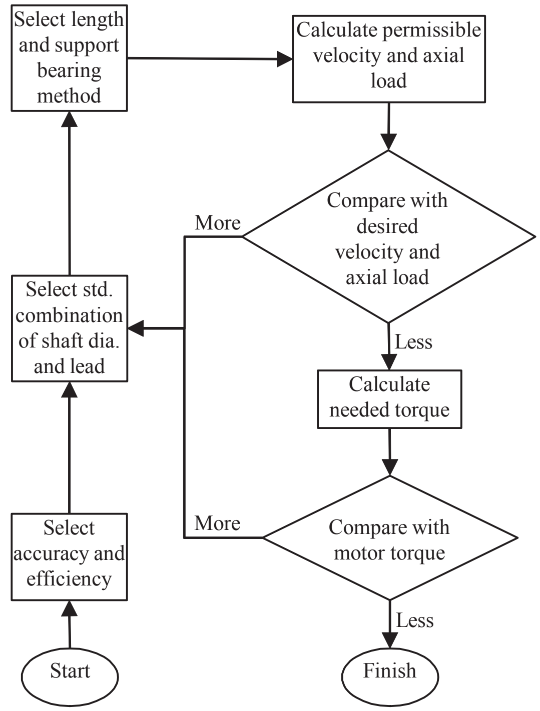


Fig. 3. Ball screw selection flowchart

mounting [13]:

- fixed-fixed
- fixed- supported
- supported-supported
- fixed-free

Among the introduced methods, fixed-supported method is utilized in the liner-rotary joint according to desired velocity and payload. Mounting type is important due to the determination of screw shaft permissible axial load and rotational speed. High axial load may cause screw shaft buckling. Considering the payload weight, applied axial load has to be less than permissible axial load [12].

Ball screw service life has to be considered similar to ordinary bearings. External load causes repeated stress on ball screw raceways and its balls. When stress reaches the limit, surface flake (scale-like pieces of metal surface) happens. Service life is the total number of revolutions that 90 % of identical ball screw units in a group achieve without developing flaking after they independently operate in the same conditions [14].

Desired end-effector linear and rotary velocities are notable parameters of the ball screw and the ball spline selection procedure. In fact the high rotational speed of screw shaft may resonate and finally become unable to operate well due to natural frequency of screw shaft [14]. The permissible rotational speed also must be checked by DN-value. This value expresses peripheral speed [12]. As shown in Fig. 5, end-effector rotary and linear motions are due to the first motor and the second motor of the linear-rotary joint, respectively. The components of the joint are shown in Fig. 5. Important parts are colored and Fig. 5-b is a cross-section of Fig. 5-a. Figs. 5-c and 5-d are closer views of screw and spline nuts which are green and blue, respectively.

Spline shaft is connected by some custom designed parts and standard bearings to ball screw nut in order to convert the motor rotation into linear motion. As shown in Fig. 5, ball spline is a guide for the ball screw. On the other hand, ball spline is responsible for the end-effector rotation. The hollow ball spline is selected to pass a vacuum tube through it. The ball spline nut is connected to the second link of the FUM SCARA robot by bearings in order to be capable of tolerating radial and axial forces.

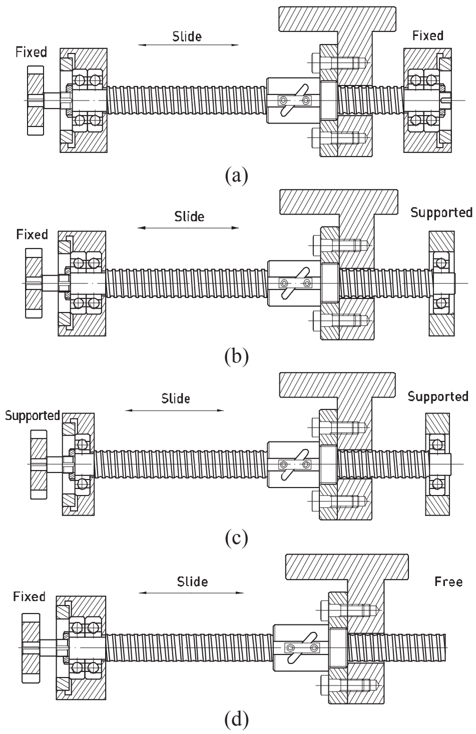


Fig. 4. Mounting methods - (a) fixed-fixed (b) fixed-supported (c) supported-supported (d) fixed-free [13]

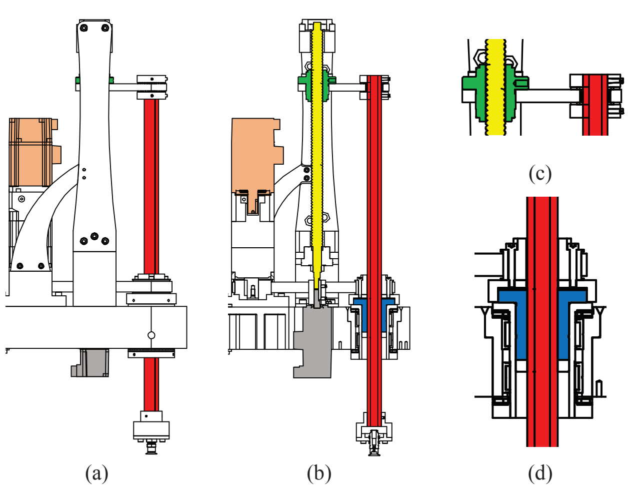


Fig. 5. Linear-rotary joint components are colored - First motor: Pink - Second motor: Grey - Spline shaft: Red - Ball spline nut: Blue - Screw shaft: Yellow - Ball screw nut: Green

IV. Cycle Time Trajectory Explanation

The criterion for power transmission system design and motor selection is the cycle time trajectory. The cycle time of SCARA robot is depicted in Fig. 6.

The cycle time is a reciprocating trajectory e.g. at the end of trajectory end-effector will return to its initial position. End-effector goes 25 mm upward then 300 mm horizontally and finally 25 mm downward [14]. This is half of the trajectory and the robot must repeat it again to get to the start point. The cycle time trajectory for the FUM SCARA robot is assumed to be 0.5 seconds. The cycle time of some famous SCARA robot manufacturers are listed in table I.

V. Workspace

Location of sensors, mechanical stops, and design of components are considered to obtain the largest possible workspace. Joint ranges of the FUM SCARA robot are listed in table II. Using these values, workspace is determined.

The Workspace of FUM SCARA robot is dexterous where the work piece could be oriented in any direction about z axis. Top view of the workspace is depicted in Fig. 7.

TABLE I. Cycle Time Comparison of FUM SCARA vs. Well Known SCARA Manufacturers

Specification	Payload	FUM SCARA	Epson LS6	OMRON R6YXG700	Adept Cobra s800
Cycle time (seconds)	0 kg	0.5			0.48
	1 kg		0.42		
	2 kg			0.42	

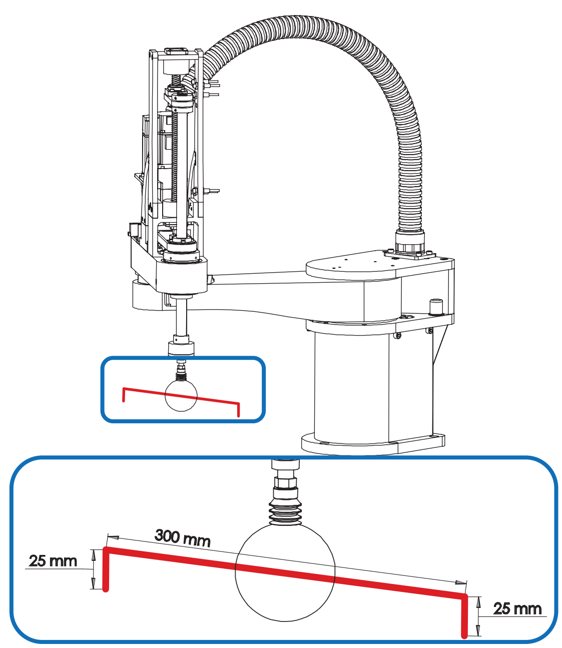


Fig. 6. Cycle time trajectory

VI. Results

ISO 9283 illustrates repeatability computation method in detail [9]. Based on ISO 9283, repeatability should be iterated 30 times in a cube which is located in the robot's workspace. The cube has two main features:

- It has to be the biggest cube located in the workspace
- Edges of the cube must be parallel to the base coordinate system

This cube is shown in Fig. 8 for FUM SCARA robot. Proposed new linear-rotary joint is applied as the third and the fourth joints of FUM SCARA. Repeatability test results of applied joint are shown in table III.

The FUM SCARA robot has traced the simulated cycle time trajectory accurately. This robot is controlled by a simple proportional-integral-derivative control method. The first, the second, and the fourth joints of the FUM SCARA are involved in cycle time trajectory. The results are shown in Fig. 9. Desired and actual trajectories are depicted by dashed and solid lines, respectively.

Fig. 9 shows that the cycle time trajectory in the robot joint space is passed with acceptable errors in desired time and the results are satisfactory.

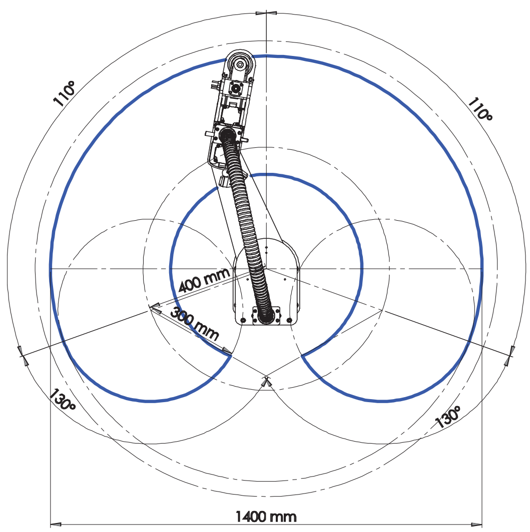


Fig. 7. FUM SCARA robot's workspace (top view)

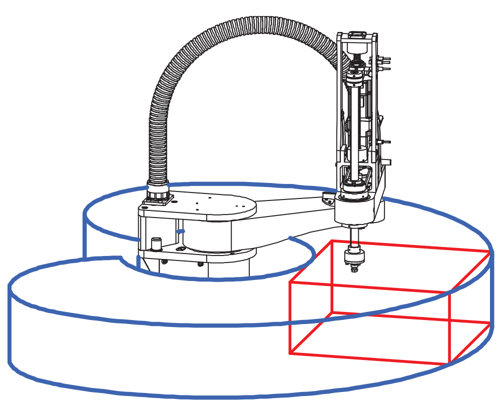


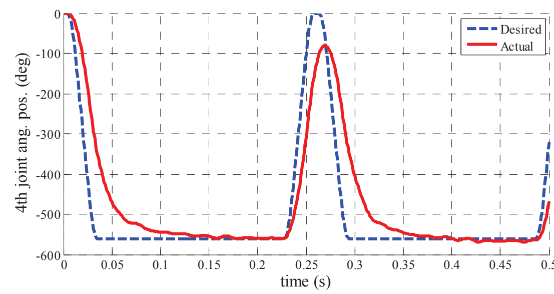
Fig. 8. Selected cube based on ISO 9283

TABLE II. FUM SCARA Workspace

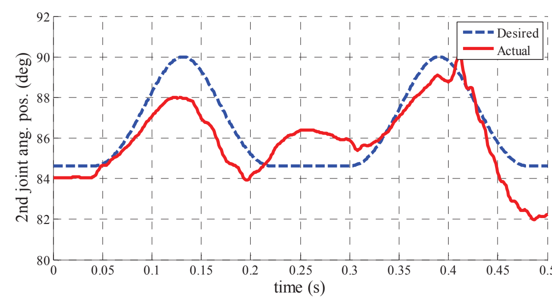
Joint	Workspace
1st	±110 °
2nd	±130 °
3rd	Unlimited
4th	190 mm

TABLE III. Repeatability of Linea-Rotary Joint

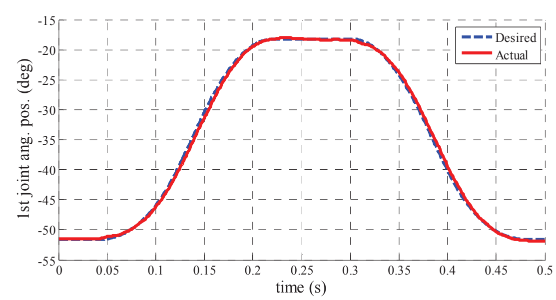
Joint	Repeatability
3rd (°)	±0.02
4th (mm)	±0.03



(a)



(b)



(c)

Fig. 9. Desired and actual joint angular position of the FUM SCARA robot racing cycle time trajectory (a) 4th joint (b) 2nd joint (c) 1st joint

VII. CONCLUSION

Details of a novel cost-effective linear-rotary joint design is first described. The joint is used on the FUM SCARA robot. Using this robot, various trajectories each having a fixed cycle time are introduced. A PID controller is used to follow the desired trajectories. Repeatability test is done based on ISO 9283 method. Results for the designed linear-rotary joint show that a satisfactory repeatability of ±0.03 mm and ±0.02 ° is obtained for its linear and rotary motion, respectively. The FUM SCARA robot offers an open architecture control system allowing the user to repeat the various tests performed in this paper using a wide variety of other control algorithms.

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