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Developing a Low-cost Rotary Series Elastic Actuator for Mechatronics Engineering Students

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Abstract: Mechatronics engineering students is taught a multidisciplinary approach for problem solving and system integration in industrial field. Students have learnt relevant subjects, but some contents are mismatched with the industrial requirements. In motion control, students should handle the vibration and external force that may occur by using various feedback control techniques. This study proposes the development of low-cost rotary series elastic actuator as a learning tool for motion control or force control. It consists of driven unit, power transmission and elastic elements connected in series that can be designed, manufactured and control by students. Not only motion control but also force control can be archived. After design and test, student will gain practical skills, how related learned subjects and solving problems.

Keywords: Series elastic actuator, learning outcome, engineering education

1. Motivation and Introduction

Mechatronics Engineering is a multi-disciplinary field of engineering that integrates the different subject areas such as mechanics, electronic, control system and computer science. Thus, students are taught a multidisciplinary approach to problem solving and systems integration, and ready to learn a new technology. Nowadays, Collaborative robot or Cobot has been introduced in the industrial applications because it performs like a traditional robot arm and safe for nearby workers. The key important technology is that applying force/torque control. Several commercial collaborative robots utilized a force/torque sensors to measure the contacting force directly for high precision result. The drawback is that the equipment cost is expensive, and it requires the specialist to operate and maintenance. Some implements the indirect force sensing method by estimating the interaction force from the displacement of elastic elements. Series Elastic Actuator (SEA) which is indirect force sensing and compliant actuator is one of interested topic for robotics engineering research because they do not only apply the motion (position/velocity) control but also the force control.

However, gap between what student have learned and what the industrial requirement was identified (Čech, M., et.al. 2019). The paper addressed that the grown of motion control technology goes faster than motion control education. For example, control courses demonstrate modelling and control design methods by using first-order or second-order system. While as the student should be prepared how to handle the vibration using feedback control techniques. To meet industrial requirements, several research works used the industrial or automotive part for education in the system dynamics topics. Ismail M.A.B et.al. (2019) proposed the using Magnetorheological suspension for studying Spencer model. McPheron, et.al. (2016) proposed the low-cost two-degree-of freedom mass-spring cart system for system identification laboratory exercise. Not only system dynamic, also the concept of force control was proposed as educational kits for students and graduated students.

HandsON-SEA which is admittance-type device, was presented to complete with the impedance-type Haptic Paddle design (Okamura, A.M., et.al., 2022) for teaching a workshop on force control (Otaran, A., et.al., 2016). Javaid, A. et.al., (2019) proposed a low-cost force feedback devices to improve learning in STEM+C. The proposed device has a larger workspace and higher force output and the ability to render free space in haptic applications. "EduExo" (2022) was also introduced as the force feedback wearable device for 1-DOF elbow joint. Both of works utilized 3D printed parts, low-cost sensors, and actuators, then the device looks affordable for students and force rendering is archived.

The previous works focuses on 1-DOF device for force control with nonindustrial parts, then students may be not familiar with the components. The systems dynamic model is modelled as lumped mass which the unmodelled behavior is not presented. In this work, the prototype of low-cost rotary series elastic actuator is described in how to design and develop with a low-cost component for mechatronic and control engineering students.

2. Conceptual framework

2.1 Learning outcome

This work proposed the design of rotary series elastic actuator to enhance mechatronics students based on relevant subjects. The basic concept of actuator design and control for students should be learned based on learning outcomes as follow:

Table 1. *Actuator Design Learning Outcome*

Course concepts	Learning outcomes
1. Principle of mechanical engineering	- Design mechanical parts, adjustable load, and elastic elements
2. Power transmission	- Design, manufacture a gear reducer - Verify prototype
3. System dynamic and control	- Synthesize the mathematical model - Design the controller gains
4. Embedded system	- Design embedded system and electronic - Write a program for embedded system - Apply a control algorithm without using library

3. Development of a low-cost rotary series elastic actuator

The rotary series elastic actuator is used as a learning tool for two-mass-spring-damping model in rotational motion and force control system. The target specification is to provide the output torque at 4 Nm in maximum, and the angular speed is limited at 180 degree/s or 30 RPM which is based on commercial Cobot specification. As shown in Figure 1, the design of rotary series elastic actuator consists of driven unit (DC brushed motor), power transmission, elastic elements, and mechanical load, which each part can be re-configured. A DC motor drives the load through the gear reducer for reducing the output speed and increasing the output torque. However, the output torque does not apply to the load directly, the elastic elements was installed between gear reducer and load to measure the interaction force which is proportional to the stiffness of torsion spring and the angular displacement. Thus, this work has two incremental encoders to measure the angular position of motor and the angular position of load. The difference between these can be estimated the static external torque by using (1)

$$T_s = K_{eq}(\theta_l - N_{-1}\theta_m) \tag{1}$$

Where T_s is the static torque/moment, K_{eq} is the equivalent stiffness of torsion spring, N is the gear ration, θ_l and θ_m are the angular position of load and motor shaft, respectively.

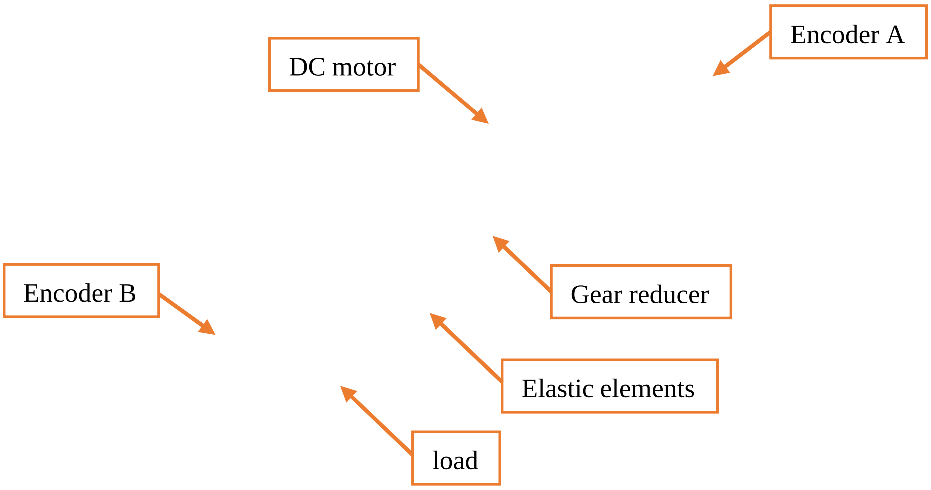
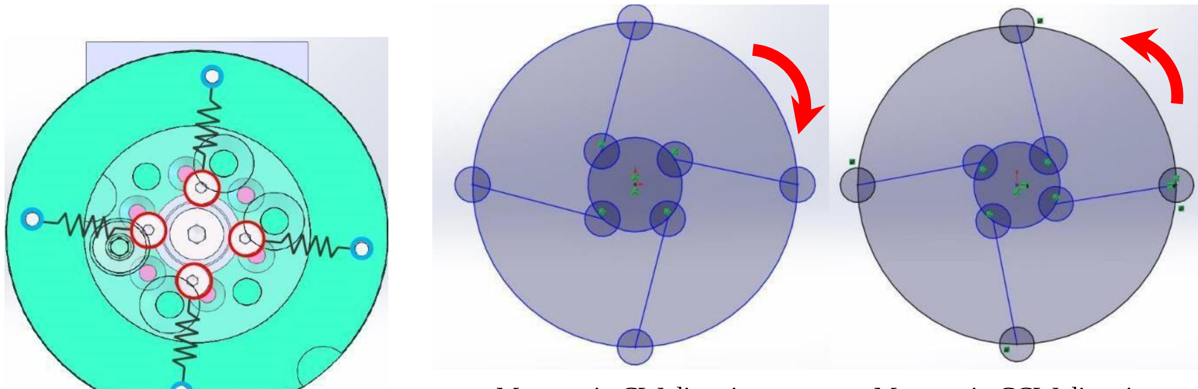


Figure 1. Components of rotary series elastic actuator.

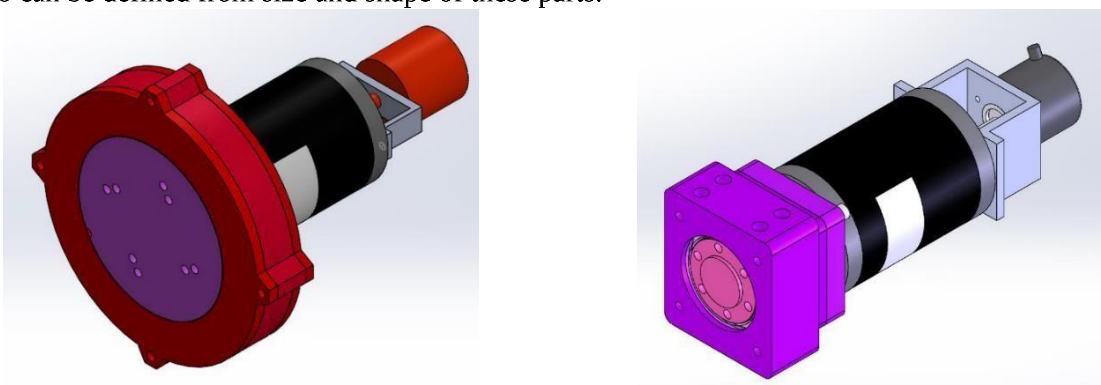
For elastic elements, students can design and select any type of elastic elements. One design consisting of four tension springs is illustrated in Figure 2, which is easy to construct but it is difficult to identify the equivalent torsion stiffness value, algebraically. Thus, they can conduct the experiment by taking the various loads and record the angle displacement.



Moment in CW direction   Moment in CCW direction

Figure 2. Elastic elements design.

For power transmission part, student can design and select type of gear reducer based on gear ratio number. The required gear ratio is calculated from the rate speed of DC motor and the required speed, then 3500/30:1 or 116:1. Considering among types of gearheads, cycloid gear reducer is high ratio in compact sizes. It has four main parts: cycloid disc, roller, output, and Crankshaft, which the gear ratio can be defined from size and shape of these parts.



a) Cycloidal Drive   b) Dual Stage Cycloidal Drive

Figure 3. Power transmission design

Figure 4. Prototypes of dual cycloid

For controller design of position and force control, student needs to find the relationship between motion and torque acted to the device. To achieve, the mathematical model of each part has been derived by a free body diagram, then MATLAB Simulink toolbox is used to simulate the system dynamic behavior and design the controller in Figure 5. By connecting signals among the block diagrams, student can easier link between actual components and system block diagram.

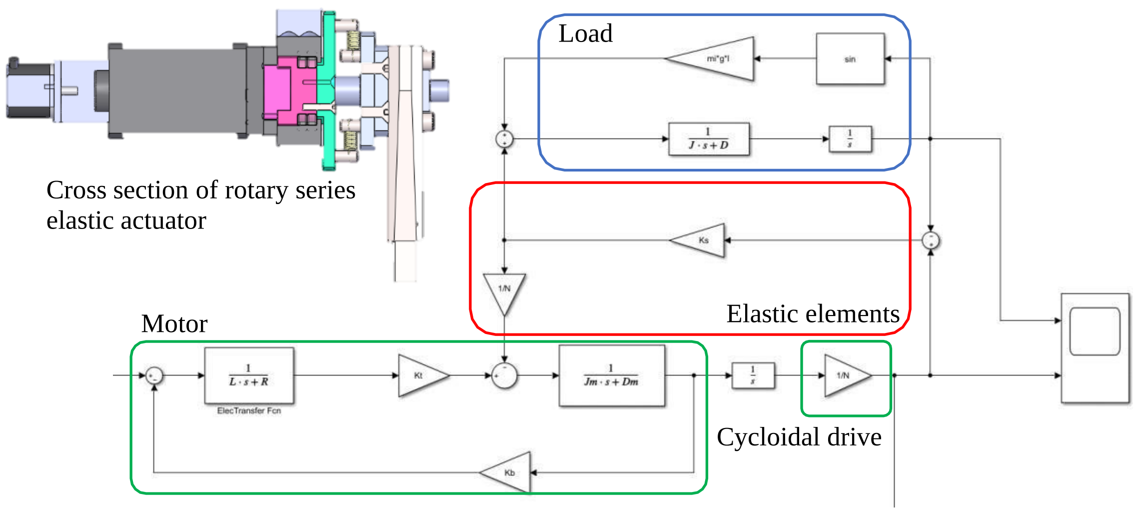


Figure 5. block diagram of rotary series elastic actuator systems

The approximate cost of protype is shown in Table 2, which is breakdown as mechanical parts, sensors, PLA filaments, electronic and microcontroller. The total cost represents the cost of new items while as students can purchase some parts for redesign which are available in the market such as PLA filament and electronic parts. By using 3D printer for building the prototype components, there is no manufacturing costs.

Table 2. *Cost of components*

Components	**Qty.**	**Net cost (USD)**
DC motor	1	25.00
Mechanical bearing	5	50.00
Tension Springs	4	20.00
Encoder	2	80.00
PLA filament for 3D printer	1	20.00
Motor Driver	1	25.00
Microcontroller board (STM32)	1	25.00
Screws, wiring cables, connectors	1	20.00
Total cost		265.00

4. Conclusion

Since the grown of motion control technology goes faster than motion control education, mechatronics engineering students have learnt the relevant subjects in the fundamental that causes the gap between the content student have learnt and industrial requirements. When students graduate, it is tough for linking their knowledge and real applications even though they have problem-solving skill and be ready adapted for a new technology. This work, we introduce a low-cost rotary series elastic actuator which involve with position control and force control. The device consists of driven unit, power transmission and elastic elements connected in series that can be designed, manufactured and control by students. Based learning outcome, students need to integrate their knowledge in principle of mechanical engineering, power transmission, system dynamic and control to model and analysis the system behavior.

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