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A Combination of a Controllable Clutch and an Oscillating Slider Crank Mechanism for Ease of Direct-Teaching with Various Payloads

Muhammad Arifin, Yuta Kage, Yuchen Yang, Alexander Schmitz, and Shigeki Sugano

Abstract— **Direct teaching is a straightforward way of teaching new motion to robots. Active methods with torque sensors, for example, can be used so that the robot can follow the movements of the human, but such methods introduce delays. Alternatively, series clutch actuators are easily backdrivable without delay. However, vertical joints are subject to gravity torques, which need to be compensated when disengaging the clutch. We implemented passive gravity compensation to counteract the robot's weight, but this mechanism cannot compensate for varying payloads, as adjustable passive gravity compensation is relatively slow and mechanically complex. The varying payload causes an unintended joint movement, i.e. the arm falls down on its own, which is unacceptable during direct teaching. Therefore, this paper demonstrates how the torque output controlled with series clutch actuators can be used to compensate for varying payloads while maintaining high backdrivability. The proposed method is evaluated on a collaborative robot with a clutch in series for each actuator. Real-world experiments with payloads from 0 to 3 kg are conducted. During the experiments, the operator force is measured to evaluate the proposed method.**

I. INTRODUCTION

Collaborative robots are expected to share their workspace with humans and work in an adaptive manner [1]. However, setting the robot up for a new task is still challenging since reprogramming the robot in a traditional manner is not trivial and time-consuming. Direct teaching was introduced to teach the robot motion for new tasks in an intuitive way [2]. In order to perform direct teaching, the robot must be compliant and easy to move during the teaching process. Active compliance using impedance control has been suggested [3] [4]. This method allows the joint to follow the external force from the operator using force/torque sensors, for example. However, controlling the joint position using a closed-loop system introduces a delay. This problem may decrease the followability of the robot positioning from the operator, for example for fast movements. On the other hand, an intrinsic actuator mechanism with high backdrivability is preferable for direct teaching. Passive compliance using series elastic actuators (SEA) was suggested to overcome this problem [5]. However, the elastic element reduces the precision during position control and leads to underdamped oscillations.

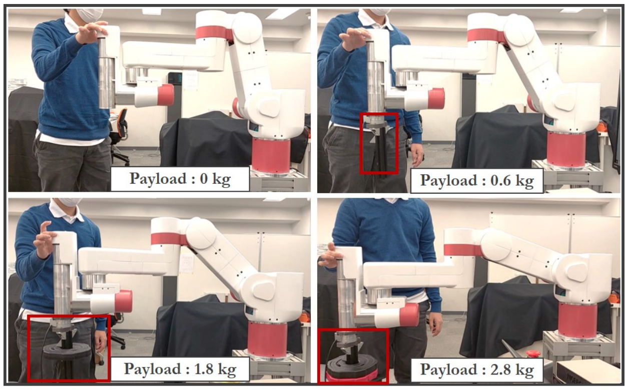

Fig. 1. Direct teaching illustration for different payloads.

Integrating a controllable clutch into the actuator, called series clutch actuator (SCA), has been proposed as an alternative [6] [7]. The clutch acts as a torque limiter for the actuator by placing it after the motor and the reducer. By setting the torque limit to zero, full backdrivability can be achieved. Therefore, the joint can be moved easily. This mechanism makes the direct teaching smooth and convenient. Several robots also have been reported to utilize this mechanism [8] [9]. The remaining problem of a SCA is that when setting the clutch to be completely opened in a vertical joint, the robot immediately collapses. This vertical joint has a large gravity torque due to the robot's own weight [10]. Therefore, gravity compensation is required to prevent the robot from falling to the ground. Considering mechanical solutions, which do not introduce any delays in the response of the robot to external forces, there are several methods to apply passive gravity compensation, based on either counterweights or springs. The counterweight method produces a compensation torque by adding or moving a weight corresponding to the gravity torque [11] [12]. This method is simple but it would increase the weight and the moment of inertia for the robot arm. Passive gravity compensation using springs can be realized without significantly affecting controllability and weight. A common mechanism exploits a tendon to compress the spring [13] [14]. This mechanism generally works well to counteract the gravity torque. However, it was confirmed that the tendon could be stretched due to holding a large force for a long time [15]. This problem leads to a decreasing compensation torque accuracy. The tendon is also possible to break, which creates a serious safety risk if humans work closely with the robot. To avoid using tendons, gravity compensation using an oscillating slider-crank counterbalance mechanism has been developed [16].

Moreover, although the gravity torque can be compensated for varying robot configurations using counterweights or

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The authors are with the Faculty of Science and Engineering, Department of Modern Mechanical Engineering, Waseda University, Tokyo 169-8555, Japan. (e-mail: arifin_muhammad@fuji.waseda.jp)

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springs, typically, passive gravity compensation only considers the self-weight of the robot and cannot compensate for varying weight of the payload. In practice, a gripper is attached to the robot and subsequently grasps a payload, which increases the robot's weight and causes an imprecise compensation. It leads an unwanted vertical joint movement following the changing gravity torque. This could interfere with the operator when teaching a complex motion to the robot and causes the possibility of having a work accident, especially in a small space. Maintaining the joint position and changing it only when the operator moves the robot is desirable for direct teaching. Furthermore, even though the weight of the payload might be small compared to the robot's weight, lifting a heavy payload still burdens the operator. Therefore, adjustable passive gravity compensation was suggested, but the existing mechanisms are complex and slow to adjust for varying weights [17] [18].

In this paper, active gravity compensation that adapts to various payloads using series clutch actuators is proposed. The clutch can adjust the torque limit for the actuator. By controlling the torque limit equal to the gravity torque, gravity compensation can be achieved. While the method is active, the operator is able to move the robot at high speeds, as the movement speed of the robot is fundamentally not limited by the proposed method.

Moreover, to allow for a small actuator and clutch, the self-weight compensation of the robot is implemented in parallel using an oscillating slider-crank counterbalance mechanism. The proposed method with clutches focuses on compensating the varying gravity torque from the payload. Finally, the system is evaluated on a collaborative robot using various payloads. The operator teaches the robot's motion by moving the vertical joint, as illustrated in Fig.1.

In the past, series clutch actuators have been implemented to ensure the safety of robots [8] [9]. To the best of the authors' knowledge, this study is the first to use a clutch for active gravity compensation for direct teaching applications.

II. PROPOSED METHODS

The combination of passive and active mechanism for gravity compensation is described. The passive mechanism was employed for compensating the self-weight of the robot. The remaining gravity torque from the payload is actively compensated with the series clutch actuator.

A. *Passive Gravity Compensation*

Modeling the gravity torque is required to design the gravity compensation. Because the robot's own weight and the kinematic are known, the gravity torque can be calculated. Fig. 2 shows the kinematic structure of our collaborative robot. A parallel linkage mechanism is used to ensure that the gravity torque on joint 2 and the next joints are independent. Basically, it can be assumed that the mass of the following links is located at the end of the link 2. The equation of the gravity torque for the gravity affected joint, which in this case is joint 2, is expressed as follows:

$$\tau_{g_2}(\theta_2) = m_2 g l_{c_2} \sin\theta_2 + (m_w + m_p) g l_2 \sin\theta_2 \tag{1}$$

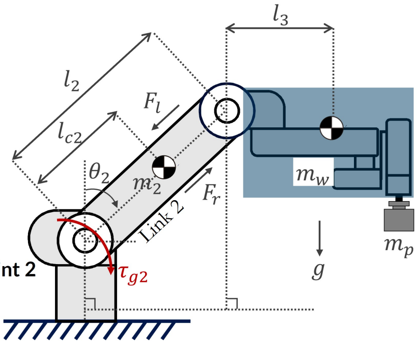


Fig. 2. Kinematic structure of the robot.

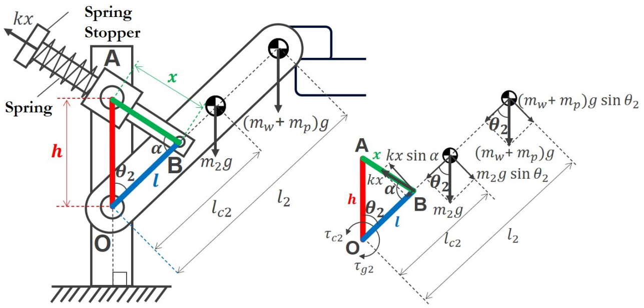


Fig. 3. Operating principle of the slider-crank mechanism.

where τ_{g_2}, m_2, m_w, m_p, g, θ_2, l_{c2}, and l_2 are the gravity torque of joint 2, the mass of joint 2, the mass of the other joints, the mass of the payload, the gravitational acceleration, the angle of joint 2, the distance between the center of rotation of joint 2 and its center of mass, and the length of link 2, respectively.

In general, the operation principle of the oscillating slider crank counterbalance mechanism is shown in Fig. 3. Here, the rotation axis of the joint 2 is O, the fixing point of the spring on the base side is A, and the fixing point of the spring on the joint 2 side is B. The compensation torque from the spring is stated by the following equation:

$$\tau_{c_2}(\theta_2) = kxl \sin\alpha \tag{2}$$

where τ_{c_2}, k, x, l and α are the produced torque from the passive compensation, the spring constant, the length of compression, the length of BO, and the angle of ABO, respectively. To perform passive self-weight compensation, the gravity torque and the compensation torque must match at any joint angle as follows:

$$m_2 g l_{c_2} \sin\theta_2 + (m_w + m_p) g l_2 \sin\theta_2 = kxl \sin\alpha \tag{3}$$

Since the α and x changes depend on the joint angle θ_2, their relation can be obtained by utilizing the cosine theorem from the triangle ABO, as follows:

$$\frac{h}{\sin\alpha} = \frac{x}{\sin\theta_2} \tag{4}$$

$$\sin\alpha = \frac{h}{x} \sin\theta_2 \tag{5}$$

TABLE I

MASS AND ARM LENGTH OF EACH PART.

Link	Distance of center of gravity from joint 2 [mm]	Mass [kg]
Second link	152.7	5.7
3rd to 6th links	330	9.7
Max. Payload	330	3.0

where h is the length of AO. By assigning (5) to (2), the compensation torque can be rearranged as:

$$\tau_{c_2}(\theta_2) = khl \sin\theta_2 \tag{6}$$

Hence, the relation of gravity torque and the compensation torque can be rewritten as the following equation:

$$m_2 g l_{c_2} \sin\theta_2 + (m_w + m_p) g l_2 \sin\theta_2 = khl \sin\theta_2 \tag{7}$$

Equation (7) can be simplified by eliminating the joint angle θ_2, as follows:

$$m_2 g l_{c_2} + (m_w + m_p) g l_2 = khl \tag{8}$$

Here, the gravity torque on the left side is a constant determined by the specifications of the robot, while the three parameters on the right side are determined to satisfy (8).

The specifications of our robot are shown in Table I. The vertical axis corresponds to the second joint in this robot. We made another design choice by compensating an additional 1.5 kg of the payload, half of the desired overall payload of 3 kg of this robot. This adjusment allows us to reduce the torque and dimension of the actuator and clutch further, i.e., ±4.85 Nm are needed to hold the payload and stop it from moving upward or downward, instead of 9.70 Nm in a single movement direction only. Based on the parameters from Table I, the gravity torque of the robot is calculated to be 44.68 Nm. To meet this torque requirement, we selected and configured the compensated parameters of k, x, h, and l to be 44.8 N/mm, 84.9 mm, 75 mm, and 13.3 mm, respectively.

B. Clutch for Direct Teaching & Payload Compensation

The mechanism of the series clutch actuators (SCA) is shown in Fig. 4. The SCA consists of a motor, a speed reducer, a clutch, and a link. The clutch is assembled between the speed reducer and the link. An electromagnetic friction clutch is used in this study. This type was reported to have a higher torque-to-weight ratio compared to MR fluid and magnetic particle clutches as well as good torque controllability [19]. This clutch mainly consists of a coil, two friction surfaces, a permanent magnet, and a leaf spring. There is a thin gap (0.2-0.3 mm) between the input and output friction surfaces when the clutch is disengaged. When voltage is applied to the clutch, the coil generates an electromagnetic field. Depending on the clutch type and the polarity of the current, the electromagnetic field can either push the friction surfaces against each other or away from each other. Thereby, one can control if the clutch is engaged or disengaged, and also how much friction the friction surfaces generate. Furthermore, when the torque difference between the input and output side exceeds the torque limit, the clutch slips and transmits the set torque limit. This feature allows the clutch to function as an adjustable torque limiter for the joint.

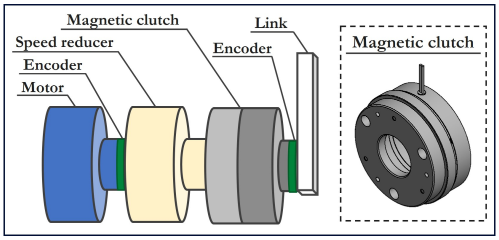


Fig. 4. Series clutch actuators joint mechanism.

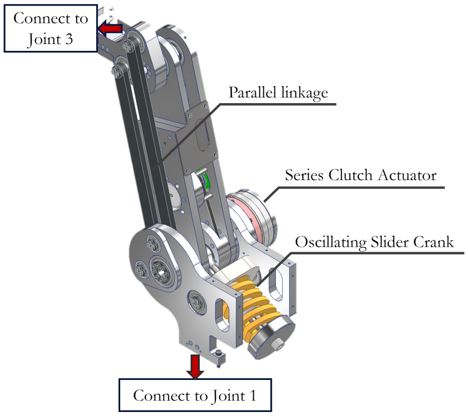


Fig. 5. gravity affected joint design with passive gravity compensation, parallel linkage mechanism and series clutch actuator.

The gravity affected joint design with the passive gravity compensation, including the parallel linkage mechanism, and the series clutch actuator is shown in Fig. 5. In our robot, the series clutch actuator and gravity compensation mechanism are introduced in parallel. The clutches are directly connected to the output side without a gearbox to achieve good torque controllability. Therefore, the torque that can be controlled with the clutch directly depends on its torque limit. The weight of the clutch used in this study is 1.4 kg, contributing only about 5.6% of the overall weight of the robot. The maximum transmission torque of the clutch is 25 Nm. This clutch is enough to lift and move the robot arm.

The gravity affected joint is passively balanced when the robot is holding 1.5 kg of payload. When putting the payload below 1.5 kg, the compensation torque from passive gravity compensation is larger than the gravity torque, causing the gravity affected joint to move upward by itself. Holding payload above 1.5 kg causes the gravity affected joint move downward. The active gravity compensation compensates for this behavior. The required torque to balance is ±4.85 Nm for no payload and maximum payload (3 kg).

The block diagram of the proposed system is shown in Fig. 6. The remaining gravity torque after subtracted the passive gravity compensation can be written as follows:

$$\tau'_{g_2}(\theta_2) = \tau_{e_2} + (m_p - 1.5) g l_2 \sin\theta_2 \tag{9}$$

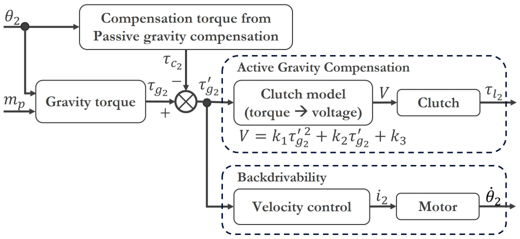


Fig. 6. Block diagram of the proposed method.

where τ_{e_2} is the error torque from the passive gravity compensation. The error torque exists due to small inaccuracies in the passive compensation parts. This error was practically observed when evaluating the passive gravity compensation, and will be discussed in section IV-A.

The remaining gravity torque becomes the reference value of the clutch to control the torque limit. Controlling the motor velocity is also essential to produce the torque and counteract the remaining gravity torque. With our clutches the transmitted torque does not depend on the slip speed, and the behavior is independent of the motor speed. However, the motor must produce torque opposite to the gravity torque. Then, if the motor produces a torque higher than the torque limit of the clutch, and the torque limit equals the gravity torque, the gravity affected joint remains stationary. When the operator applies forces to the joint to move it, this only alters the slip speed, but the joint is easy to move in both directions, as long as the motor moves the link faster than the human. Ensuring good durability and reproducibility of the torque limit is essential for our method, and these aspects will be further investigated in future studies.

The control system for the clutches requires as input only the payload and the current joint angle, but there is no feedback system for the clutches such as slip speed or force feedback. The clutch control itself is an open-loop system. To control the torque limit clutch, a transfer function of reference torque to voltage is required. A simple model to achieve the model-based open-loop torque limit of the clutch is utilized. The torque is modeled as a quadratic function dependent on the voltage. The relation between the voltage and the torque limit can be stated as follows:

$$v = k_1\tau'^2_{g_2} + k_2\tau'_{g_2} + k_3 \tag{10}$$

where the parameters k_1, k_2, and k_3 are the parameter models of the quadratic function.

III. EXPERIMENTAL SETUP

A collaborative robot called Nicebot-5 is used to verify the proposed method. The robot has a clutch in series on each actuator without torque sensor. A gravity affected joint of this robot (joint 2) is tested to validate the proposed system. The operation range of this joint is 0° (pointing straight up) - 135°. To achieve easy backdrivability, the motor is configured to run at 1600 rpm for the continuously slipping clutch. Because the reduction ratio of the speed reducer is 1:200, the link speed reduces to 8 rpm. The motor direction is controlled depending on the torque requirement of joint 2.

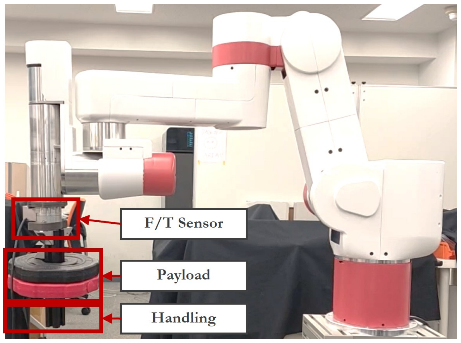


Fig. 7. Experimental setup of the robot. Note that the F/T sensor is utilized only to evaluate the proposed system.

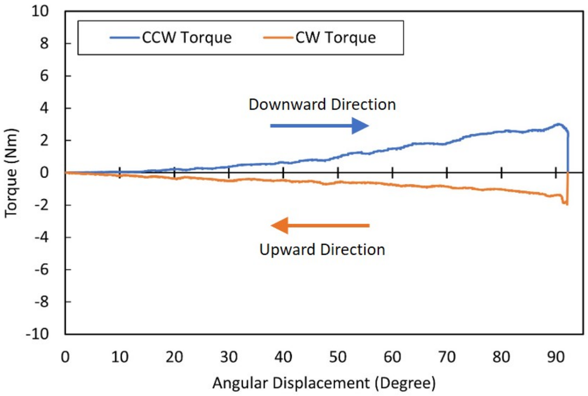


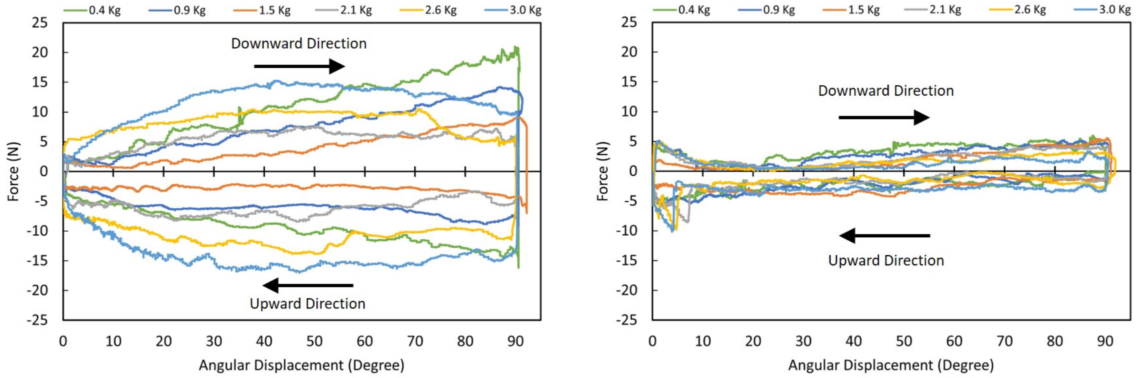
Fig. 8. The torque results of passive gravity compensation when moving the gravity affected joint (θ_2).

A 6-axis F/T sensor (PFS055YA251 from Leptrino) is utilized to evaluate the proposed method. This sensor measures the operator force when moving the gravity affected joint. The sensor is attached to the end-effector of the robot, as shown in Fig. 7. Because the sensor is put before the payload, the initial reading of the sensor is not zero due to gravity. Offsetting the sensor is required by subtracting the baseline from the sensor readings. The weight of the F/T Sensor is included in the payload for the robot in all experiments.

IV. EVALUATION

A. Self-weight Compensation

The passive gravity compensation using the oscillating slider-crank counterbalance mechanism was evaluated by practically measuring the torque. This torque is calculated from the force of the F/T sensor and the robot posture. The evaluation experiment was carried out by adding the 1.5 kg payload to the robot based on the parameter design in Section II-A. The torque was measured by slowly moving the joint from 0° to 90° (downward) and back to 0° (upward). During this experiment, the clutch of the joint was disengaged so that the compensation mechanism had no interference from the motor and the torque limit of the clutch.



(a)

(b)

Fig. 9. Required force of the operator to move the gravity affected joint (θ_2): (a) without active gravity compensation, the force increased depending on the payload, (b) with active gravity compensation, the force was significantly reduced and gave the same results for different payloads

Fig. 8 shows the torque results of the gravity affected joint with passive gravity compensation. The results show that the compensation mechanism successfully reduces the gravity torque from 44.68 Nm (theory calculation from section II-A) to 3.01 Nm. The reduction rate of the passive gravity compensation is 93.27% with an average torque of 0.76 Nm. The operator can easily move the gravity affected joint without needing to lift the weight of the robot. It shows that the compensation mechanism could nearly produce and counteract the gravity torque from the overall weight of the robot. However, a slight torque needs to be overcome when moving the joint due to the compensation error. This compensation error seems to be due to the constant spring error and the machining accuracy of the parts, such as bearings and linear bushings.

B. Direct Teaching with Various Payloads

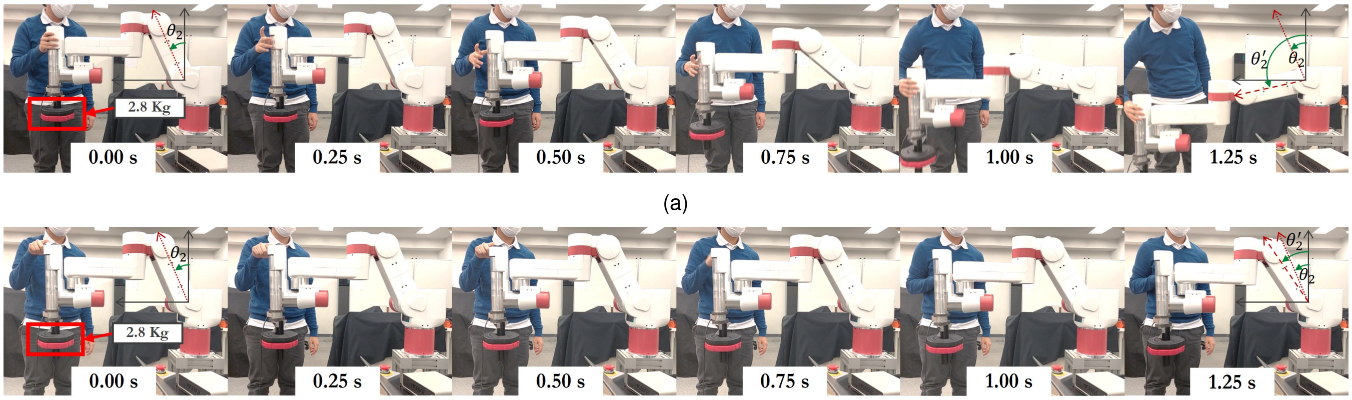
The active gravity compensation (AGC) was verified through direct teaching with a variety of payloads. The clutch of joint 2 in this robot was controlled to actively compensate for the gravity torque according to the payload. During this experiment, the operator moved the joint handle slowly from 0° to 90° (downward) and back to 0° (upward) in 20 seconds. Furthermore, direct teaching without AGC was also conducted as a comparison to the proposed method.

Fig. 9 shows the comparison force results to move the gravity affected joint when loading with different payloads: 0.4 kg, 0.9 kg, 1.5 kg, 2.1 kg, 2.6 kg, and 3.0 kg. Without active gravity compensation, the operator force increased depending on the payload, as shown in Fig. 9a. Although the gravity torque has been reduced from the passive gravity compensation, the remaining gravity torque caused by the payload is still high. Consequently, the robot fell down immediately after the operator released the joint. For most payloads, the position at 90° requires a lower force than at 45° due to imperfect passive gravity compensation, as also shown in Fig. 8. There was a compensation error and over-compensation starting from 45°, which caused a decrease in the operator's force. Using the same configuration, direct teaching with active gravity compensation can greatly reduce the operator force, as shown in Fig. 9b. Interestingly, the data shows the same average torque results (2-3 N) and curve trendline for different payloads. The required force significantly decreased, with the highest reduction rate of 79.27% in this experiment. The average required force for all payloads was calculated as 2.6 N.

Below 5°, a relatively large force was necessary to move the robot. This happened because the magnetic field of the clutch was too small to engage the friction surfaces so that the clutch cannot adjust the torque limit from 0 to 1.52 Nm [19]. Because our goal is to balance the joint in any position for direct teaching, we set a constant torque limit of 1.52 Nm and stop the motor when the gravity torque is below 1.52 Nm. This method successfully achieves a stable joint position, but it requires a higher force to move the robot, particularly in the direction opposite to gravity, as shown in Fig. 9b. If we disregard the force below 5°, the required force reduced by 81.66%. The mechanism cannot completely reduce the gravity torque to zero because of the friction torque in the joint mechanism and the inaccurate torque limit of the clutch model. However, this average force (2.23 N) is small enough and within a reasonable range for humans to move the joint of the robot for direct teaching.

Furthermore, the backdrivability and the joint balance were assessed. The force was collected from 0° to 90° and back to 0°, but the joint was not moved continuously. The operator released the robot in a random position and grabbed it again to check whether the joint kept the last teaching position or not. Fig. 10 shows the operator moving the gravity affected joint when the robot held the payload. In Fig. 10a, when not applying for the active gravity compensation, the robot fell down immediately after the operator released the joint. The final position (θ_2) would be more than 90° if the operator did not stop the robot. Fig. 10b shows that the robot did not fall down and kept the last teaching position (θ_2) after the operator released the joint using the same payload (2.8 kg). Furthermore, moving the gravity affected joint was easy by using just 1 or 2 fingers.

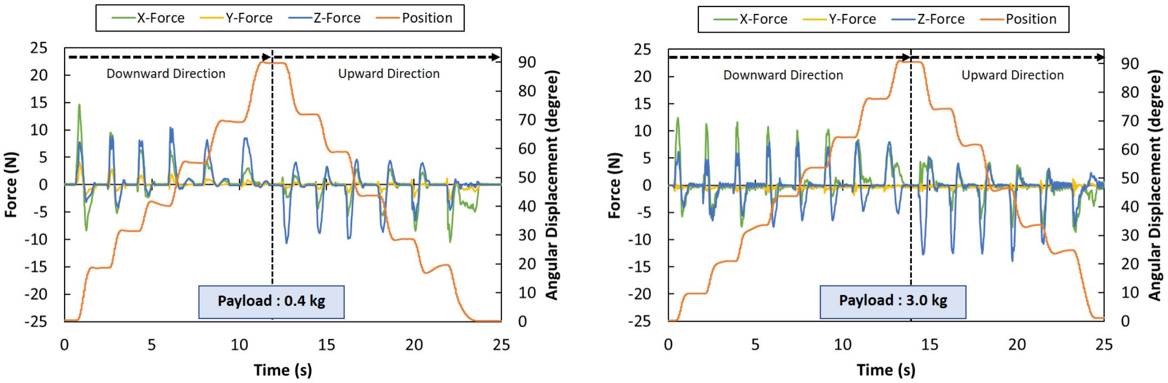
The operator force to backdrive the joint and the angular displacement are shown in Fig. 11. The operator grabbed



(a)

(b)

Fig. 10. Direct teaching performance on the gravity affected joint (θ_2) : (a) without active gravity compensation, the robot fell down immediately after the operator released the robot, (b) with active gravity compensation, the robot kept the last teaching position, and it was easy to move the joint by using 1 or 2 fingers.



(a)

(b)

Fig. 11. Backdrivability force: (a) tested with a payload of 0.4 kg, (b) tested with a payload of 3.0 kg

the bar to measure the force for this experiment. This graph displays the outcomes for 0.4 kg and 3 kg payloads. As can be seen, no force was required to maintain the joint position for any payload by the operator. Additionally, the robot only moved when it received an external force. This shows that the robot was compliant to move. There was a significant peak and valley force when moving the robot. This value occurred due to the initial force needed to overcome inertia when starting and stopping the joint. By using the suggested techniques, the robot adhered to the operator's external force and maintained the last teaching position whenever the operator released the joint. Even for different payloads, the clutch can quickly change the torque limit to account for the gravitational torque.

V. CONCLUSION

This study proposed the combination of controllable clutch and the oscillating slider-crank mechanism to compensate the gravity torque in any payload for ease of direct teaching. The clutch manages to compensate for the changing gravity torque from the payload. The self-weight of the robot has been compensated separately by using an oscillating slider-crank counterbalance mechanism, which results in reducing the gravity torque by 93.27%. The torque limit of the clutch is controlled by using an open-loop system and modeled with a quadratic function. This system enables the clutch to quickly adjust the torque limit following the changing gravity torque due to the payload.

The evaluation indicated that the clutch successfully compensates for the gravity torque and the same torque is required to move the robot regardless of the payload. The robot did not fall down and kept the last teaching position even though the payload was different. Moving the gravity affected joint was easy, with the average force operator measured at 2.6 N. The operator force was reduced by 79.27% compared to direct teaching without the proposed method. The robot can be moved by using only one finger.

In future work, the full gravity compensation, including the self-weight of the robot using only series clutch actuators will be developed. However, the clutch with high torque limits, small dimensions, and lightweight is not available in the market. A mechanism to increase the clutch torque limit will be studied. Furthermore, the robot should know the payload beforehand to adjust the torque limit accordingly. Estimating the weight is the next step to achieve automatic adjustment for an unknown payload [20].

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