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Development and Evaluation of a Linear Series Clutch Actuator for Vertical Joint Application with Static Balancing

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***Abstract*— Future robots are expected to share their workspace with humans. Controlling and limiting the forces that such robots exert on their environment is crucial. While force control can be achieved actively with the help of force sensing, passive mechanisms have no time delay in their response to external forces, and would therefore be preferable. Series clutch actuators can be used to achieve high levels of safety and backdrivability. This work presents the first implementation of a linear series clutch actuator. It can exert forces of more than 110N while weighing less than 2kg. Force controllability and safety are demonstrated. Static balancing, which is important for the application in a vertical joint, is also implemented. The power consumption is evaluated, and for a payload of 3kg and with the maximum speed of 94mm/s, the power consumed by the actuator is 11W. Overall, a practical implementation of a linear series clutch actuator is reported, which can be used for future collaborative robots.**

I. INTRODUCTION

Robots are expected to increasingly work together with humans. Such collaborative robots are not only expected to be (1) safe around humans, but also to be (2) easily backdrivable, which can be used for direct teaching of trajectories to the robot, and furthermore in general such robots should be (3) force controlled, so that they can adapt better to changing environments. To achieve these kinds of characteristics, most commercially available collaborative robots measure the forces acting on the robot [1][2][3]. However, precise sensing and good models of the robot dynamics are required, and, more importantly, such active force control always introduces a time delay between the external forces acting on the robot and the robot reacting to them.

Passive mechanisms have no time delay, and would therefore be preferable. Some actuators, such as direct drive electric motors, are mechanically backdrivable, and force control can be achieved with high fidelity by controlling their motor current. However, such actuators tend to be bulky and heavy. Therefore, to achieve lighter and more efficient actuation, often speed reducers are used, which limit the passive backdrivability of the actuator. Series elastic actuators (SEA) [4][15] use an elastic element, typically a spring, which can absorb impact energy and gives the robot overall a softer characteristic. However, the position control bandwidth of SEAs is reduced, which limits their application for robot arms outside the academic community. Moreover, to control the forces that the SEA exerts, the spring deformation needs to be controlled, and fast control is required for dynamic contact scenarios. Actuators with adjustable spring stiffness can optimize the trade-off between fast position control and passive compliance depending on the situation in which the robot finds itself in, but such systems do not only tend to be bulky but also do not solve the fundamental disadvantages of SEAs.

Series clutch actuators can achieve all three characteristics described above. Their torque limit can be set at each time step, so that they act like an adjustable, passive torque setting device, which guarantees safety and can be used to control the output torque. When setting the torque limit to zero, they become easily backdrivable. They become a perfect torque source, while the additional clutch only adds a reasonable amount of weight and power consumption to the system, as will also be demonstrated in this paper.

To the best of the authors' knowledge, in the past series clutch actuators have only been implemented in rotary actuators. Linear actuators are required for many robot configurations. The linear actuator in this paper was specifically designed as a vertical linear joint, for example in a Cartesian or SCARA robot. While it would have been possible to directly implement a linear clutch to the system, a rotary clutch can be more compact and lightweight. The paper discusses several methods to achieve linear actuation from an otherwise rotary actuator. In particular, we implemented a simple rack and pinion system, which is relatively lightweight and efficient, maintains the easy backdrivability of the system, and its main drawback (backlash) is not as relevant for a vertical joint, as gravity always pulls on the output.

While it is straightforward to achieve backdrivability for the actuator, this is not sufficient for direct teaching. In particular, the user would always have to lift the weight of the actuator and the payload. However, this paper also demonstrates how the force controlled by the clutch can be used to statically balance the load, while maintaining easy backdrivability.

Like in our previous work [6][10][16][18], we use electromagnetically controlled friction clutches, as they achieve a high torque-to-weight ratio and demonstrated their excellent torque controllability. Unlike in our previous work, we use a clutch that is closed without power, and which reduces its torque limit as power is applied to its electromagnet. When used for a vertical joint this is important to avoid that

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the mechanism's output side falls down in case of a power outage.

Thus, the main contributions of this paper are: for the first time a linear clutch actuator is implemented. Its force controllability and safety are demonstrated. Static balancing was implemented for the first time purely by using the clutch. The power consumption is evaluated. Overall, for the first time a practical implementation of a linear clutch actuator is reported, which can be used for collaborative robots in the future.

The rest of this paper is structured as follows. Section II reviews related work on linear actuators and series clutch actuators. Section III describes the implementation of the linear clutch actuator, and discusses in particular the choice of the rack and pinion system and of the clutch. Section IV discusses the implementation of the actuator's backdrivability and static balancing. Section V explains the experimental setup. Section VI presents results on the actuator's force output controllability, backdrivability and static balancing, safety, and power consumption. Section VII draws conclusions and discusses possible future work.

II. RELATED WORKS

Most linear electric actuators use rotary motors with an additional mechanism to convert the rotary motion to a linear one, typically a lead screw. Ball screws have a better backdrivability than lead screws, but ball screws with reasonable reduction ratios still have limited backdrivability. Relatively high reduction ratios are necessary so that the electric motor can run at efficient speeds, and so that relatively small sized electric motors can be used.

Purely linear electric actuators exist, such as solenoids, and while they have a perfect backdrivability, they are heavy and large-sized for their force output. Cooling systems can allow an actuator to achieve higher force output, but such cooling systems add to the size and complexity of the actuator and can only increase the force output of the actuator to a limited extend. In [21] a direct drive motor with a relatively high force-to-weight ratio is reported, i.e. it can produce 1000N nominal force with a weight of 77 kg. The force-to-weight ratio is therefore 12 N/kg, which is much lower than the force to weight ratio of the actuator reported in the current paper, i.e. 112 N/1.95 kg = 57.4 N/kg. [12] describes an internal permanent magnet vernier motor. While it is perfectly backdrivable, the maximum output force is only 14N and the maximum speed is 23mm/s. For industrial robots, often higher payloads are required, and the challenge is to achieve safety, backdrivability, high force capacity and compactness concurrently.

Pneumatic and hydraulic actuators can achieve linear actuation in more compact form factors, but require additional compressors or pumps and the entire circuitry to circulate the air or fluid, respectively. Also, their backdrivability is limited. [13][14] are linear actuators that are backdrivable to some extent, using magnetorheological (MRF) fluid. The force output of [13] is 14N, and it tends to heat up. The system described in [14] is bulky, and its backdrivability is limited. In general,

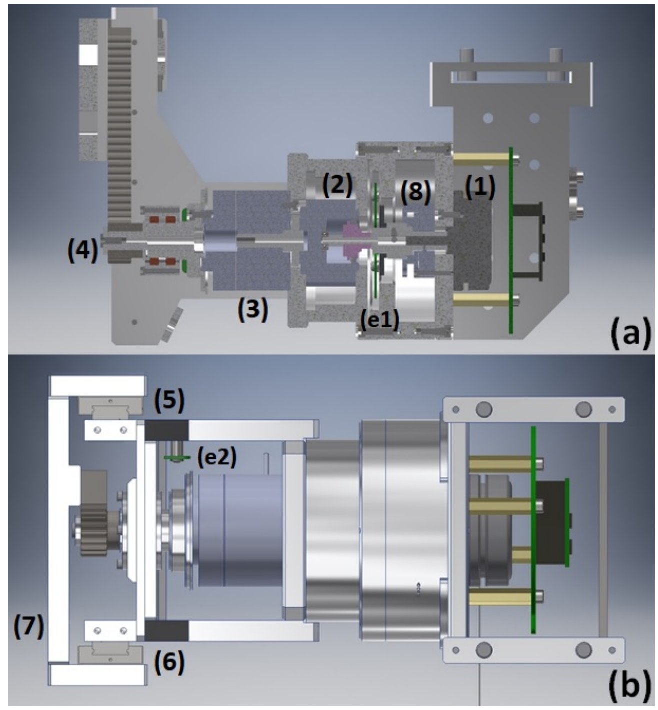

Fig. 1. 3D model of linear actuator design: (a) cut section side view, (b) top view. The electric motor (1) is connected to the harmonic drive (2), which acts as the speed reducer. It is then connected to the clutch (3), and finally a rack and pinion gear pair (4) converts rotary motion to linear motion. (5) and (6) are linear guides to support the linear movement. (7) is the output attachment. (8) is the motor brake. (e1) is the encoder before the clutch and (e2) is the encoder after the clutch.

in addition to their limited backdrivability, hydraulic systems have practical problems, from maintenance, and leakages to the overall safety of the system.

Overall, existing systems, unless they are bulky and heavy, have limited backdrivability. We argue that higher levels of backdrivability, and therefore better safety and easier direct teaching, can be achieved with series clutch actuators (SCAs). In the past only rotary SCAs have been implemented. Such actuators have been implemented using MR fluid [7][8][9] or friction surfaces [5][20]. Our lab has shown that electromagnetically controlled friction clutches achieve a good torque-to-weight ratio and also a good torque controllability [18].

III. SYSTEM DESIGN AND IMPLEMENTATION

In this section, the design and implementation of the linear series clutch actuator is explained. The clutch available for our design is a rotary element, which is otherwise used for rotary actuators in our lab. The development of a new linear clutch would not only have been time and cost consuming, but, more importantly, a linear clutch would be heavier and bulkier than its rotary counterpart, as it would need to cover the entire stroke of the actuator. Therefore, the implementation of the concept is as follows: a prime mover (electric motor), followed by a speed reducer, then the rotary clutch to control the power transmission to the output, and finally a mechanism to convert the torque into a linear force.

Fig. 1 shows the 3D model of the prototype that we developed to evaluate the performance of this concept. The prime mover, an electric motor (1), is connected to the harmonic drive (2), which acts as a speed reducer, with a reduction ratio of 30 : 1. The harmonic drive connects to the clutch (3), and finally, there is the rack and pinion gear pair (4) to convert the rotational motion into linear motion. Hence, the design follows the previously described, 'Prime mover - Reduction - Clutch - Mechanism for conversion of rotary motion to linear motion' pattern. There are two linear bearings (5) and (6) respectively, to support the linear movement. Finally, there is a provision to connect to the output (for example a gripper or payload) (7). (8) is a power-off motor brake. The motor brake ensures that the motor cannot be backdriven in the case of a power outage. Considering the future implementation of the actuator in a robot, we have put two encoders (e1) and (e2) before and after the clutch respectively in the actuator for position control.

The motor torque is transmitted to the clutch through the harmonic drive, and finally through the clutch to the pinion. The prototype is designed for a continuous payload capacity of 3 kg. We have used an 18 teeth pinion with module 1. Therefore, the pitch circle diameter of the pinion is 18 mm, and for a payload of 3 kg ($\sim$30 N), a minimum of 270 mN-m torque is required. Considering the reduction of the harmonic drive (30:1) and a conservative estimate of the efficiency of the harmonic drive (0.6 [17]), the required input torque of the motor is 15 mN-m. We have used a Maxon 30W brushless DC motor for the prototype in this paper. Its rated torque is approximately 55 mN-m. The speed reducer is a CSF-8-30-1U-CC-F unit type harmonic drive, with a rated torque of 0.9 N-m. The specifications of the prototype are listed in Table I.

TABLE I

SPECIFICATIONS OF THE PROTOTYPE

Payload Capacity	3 kg
Dimensions	221.5 mm x 119 mm x 150 mm
Weight	1.95 kg
Stroke	100 mm
Speed	94 mm/s

A. Selection of Rack and Pinion

There are many alternative methods to convert a rotary motion to linear motion. We will discuss some of the possible alternatives, and explain our reasons for selecting a rack and pinion over those alternatives. Broadly speaking, there are three basic options - mechanical linkage, nut-screw or gears.

For a mechanical linkage, three options were considered. The first is a slider-crank mechanism. For a desired stroke of 100 mm, the crank would need to have a length of 50 mm, which would have increased the size of our overall design. Moreover, both the force and velocity of the slider depend on the crank angle, i.e. they are not linear. The second option is a scissor mechanism, but it requires rather big bearings to

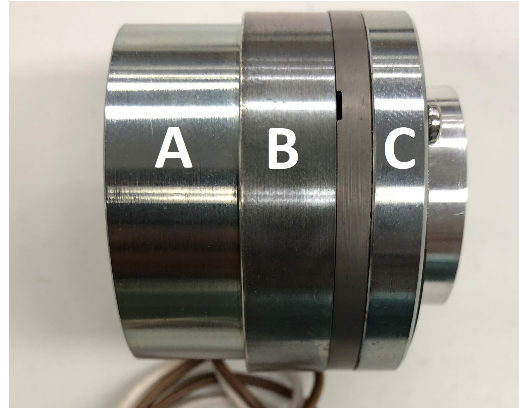

Fig. 2. Clutch used in the prototype. Part A contains the coil for the electromagnet. Part B has the input friction surface. Part C consists of the output friction surface and the permanent magnet.

have a reasonable operational lifetime. The third option is a Scotch-Yoke mechanism, which has the same downsides as discussed for the slider-crank linkage.

For the nut-screw option, there are two alternatives - lead screw and ball screw. Lead screw is a popular method of converting a rotary motion to linear motion, but it is not backdrivable, and was therefore discarded. A ball screw is backdrivable, but depending on the lead angle, to a lesser degree than a rack and pinion system. Furthermore, it is overall more complex than a rack and pinion system. On the positive side, it has less backlash than a rack and pinion system, and it would be a strong alternative, depending on the desired form factor and application. Given however that we want an actuator that is aligned horizontally and moves vertically, we concluded that a rack and pinion system achieves our desired purpose in a simpler and more lightweight fashion, as explained below.

Finally, two types of gears convert rotary motion to linear motion, a worm gear and rack & pinion. A worm gear is not backdrivable, and therefore not suitable for our application. Rack and pinion is a simple, cheap, lightweight and easily backdrivable mechanism. The main drawback of rack and pinion, backlash, is not as relevant in our application as a vertical joint, as gravity always pulls the output downwards. Overall, rack and pinion was chosen due to the easy and compact implementation it allows.

B. Selection of Clutch

For this design, we have used an electromagnetic friction clutch. It consists of a permanent magnet attached to the output friction surface of the clutch, and a coil next to the input friction surface of the clutch. The coil generates an electromagnetic field when voltage is applied across it. Depending on the polarity of the voltage, the electromagnetic field developed by the coil either strengthens or weakens the magnetic field of the permanent magnet, and the clutch either tends to engage or disengage respectively. The reason of using a normally engaged clutch is, with a normally disengaging clutch, the mechanism will fall down by its own weight when there is no power. Maximum 24volts can be applied across the clutch. The maximum torque transmission capacity of the clutch is 1N-m. The clutch itself weighs only 0.27 kg, and contributes therefore only about 14% to the overall weight of the actuator.

As shown in Fig. 2, the clutch has three parts. Part A consists of the coil. Part B is the input of the clutch, and has the input friction surface. It is made of a ferromagnetic material, which is attracted to the permanent magnet. Part C is the output of the clutch. It contains the permanent magnet. The clutch has zero backlash, and therefore the clutch does not impede the position controllability of the overall system.

IV. Backdrivability and Static Balancing

It is straightforward to achieve backdrivability of our actuator by setting the torque limit of the clutch to a minimum. For a horizontal joint, backdrivability is sufficient to enable direct teaching. However, for a vertical joint, the weight of the payload and of the output side of the actuator would always apply a force downwards. Therefore, the user would always have to lift this weight when direct teaching the system. Static balancing of the system is required.

Static balancing can be achieved passively, with counterweights or springs [11], which however adds complexity and weight to the actuator. Therefore, this paper demonstrates how the force controlled by the clutch can be used to statically balance the load.

The transmitted torque of our clutch can be controlled by setting the voltage applied to the electromagnet. The slip speed only influences the transmitted torque to a neglectable degree. However, depending if the speed of the input side of the clutch is faster or slower than the output side, force is produced either upwards or downwards. The speed of the input side of the clutch is determined by the speed of the motor, the speed of the output side of the clutch is determined by the user who performs direct teaching.

To statically balance the load, and to allow easy direct teaching, basically, the force produced by the payload must be counterbalanced by the force transmitted by the clutch, as shown in Fig. 3. Therefore, the clutch is set at the torque corresponding to the torque produced by the payload. The motor moves with a constant speed (turning direction corresponding to moving the rack upwards), which has to be faster than the speed that the human produces when backdriving the system. Thereby it can be guaranteed that the force transmitted through the clutch only produces upward thrust. In particular, if the motor would not move or moves slower than the speed produced by backdriving the system, and the human moves the rack upwards, the clutch would produce a thrust in the downward direction, thereby opposing instead of assisting the human to lift the payload. If the motor moves fast enough, and the clutch is set to the correct torque limit, a user can easily move the payload in both the upward and downward direction.

Therefore, to achieve the static balancing, while the actuator is in operation, we produce the upward thrust by continuously slipping the clutch input against the clutch output. As shown in Fig. 4(a) and Fig. 4(b), the input friction surface is continuously slipped against the output friction surface. This slipping produces an upward thrust to balance the payload, as shown in Fig. 3. Upward thrust is continuously produced by slipping, and therefore it requires very little force to backdrive the mechanism, giving easy backdrivability to the actuator, as will be evaluated in Section VI-B.

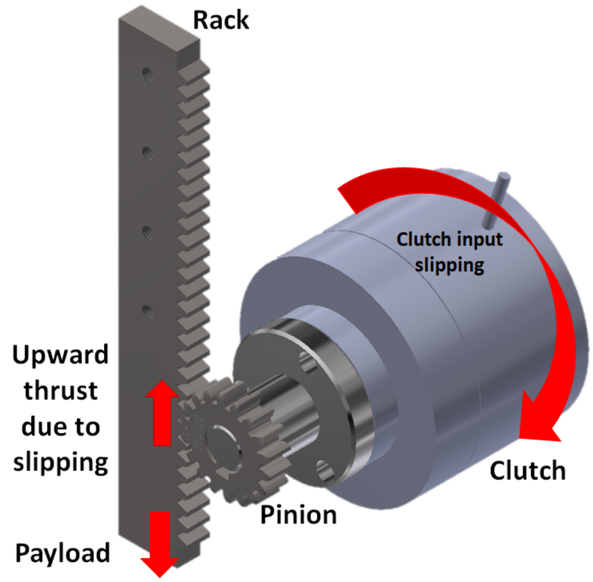

Fig. 3. Static balancing of the linear actuator by slipping the clutch. The friction force of slipping the clutch generates thrust, which balances the payload and the moving mass of the actuator.

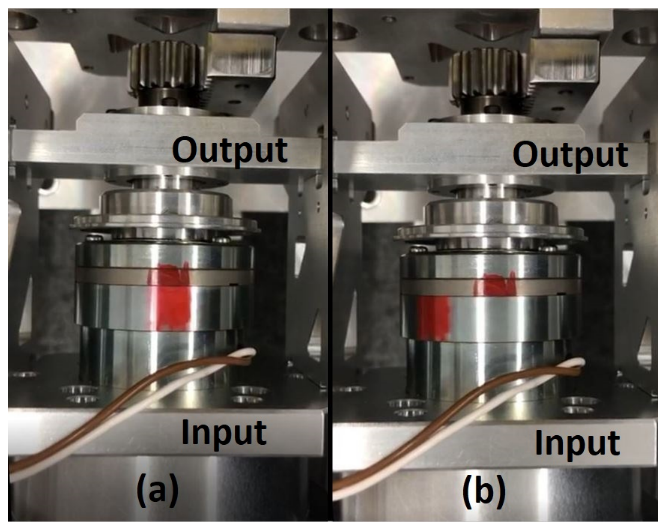

Fig. 4. Slipping of the Clutch. The relative movement of the input friction surface of the clutch with respect to the output friction surface can be seen in (a) and (b).

V. EXPERIMENTAL SETUP

Fig. 5(a) and Fig. 5(b) show the experimental setup for evaluation of the prototype. The prototype is rigidly mounted on a heavy structure to make sure that the system remains

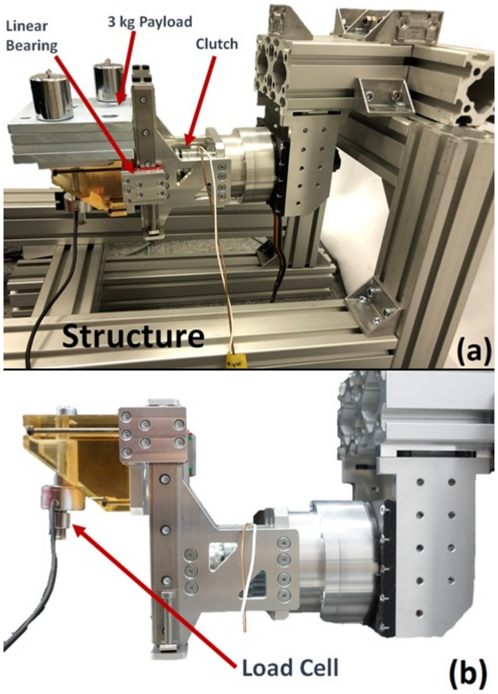

Fig. 5. Test setup. (a) Actuator prototype rigidly attached to a heavy structure; furthermore, the payload of 3kg can be seen. (b) A force sensor is mounted on the output to measure the force output.

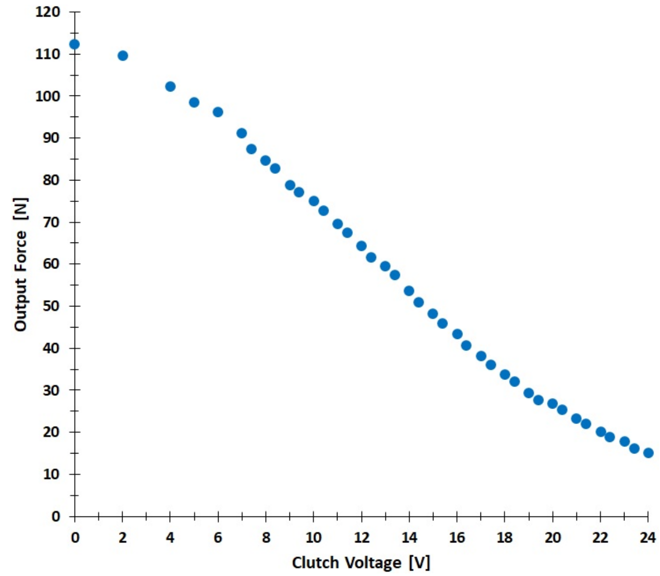

Fig. 6. Force output. Relationship between clutch voltage and force output of the actuator. The force output decreases almost linearly with an increase in clutch voltage.

stable during the testing, and does not tilt or lift itself because of the force exerted by the actuator. The actuator can be loaded as shown in Fig. 5(a), in which 3 kg payload can be seen.

A load cell is mounted on the actuator to measure force output. The force output data can be observed on a voltage amplifier. The load cell is calibrated such that it outputs 0.237 volts when 10 N is exerted on it. An analog to digital converter - USB6001 from National Instruments was also used to record the real time voltage data from the load cell to plot the time curves. The voltage output of the load cell was measured at a sampling rate of 1 kHz during the experiments.

We used a Maxon brushless DC motor with a built-in encoder, which was controlled with an EPOS 2 50/10. During the experiments, the only parameter of the motor that we controlled is the speed. The clutch is connected to a power supply, capable of supplying 24 volts. The voltage of the clutch is varied manually, since we wanted to measure force output of the actuator at different voltage levels of the clutch. All the experiments were carried out with the described test setup.

VI. EVALUATION

In this section, we will present the evaluation of the proposed linear series clutch actuator and the results obtained. The actuator is evaluated for the following criteria -

- Force output
- Backdrivability & static balancing
- Impact force
- Power consumption

A. Force Output Test

This experiment is performed to determine the force output and nature of change of force output with respect to change in clutch voltage. For this experiment, the motor was run at a constant speed. The force exerted by the actuator on a rigid surface was measured for different clutch voltages. We measure force starting from the voltage where the torque transmission limit of the clutch is lowest, that is at 24 volts, and stop measuring the force when the output exceeds either the actuator's maximum force capacity or the torque transmission capacity of the clutch. The velocity of the actuator was set to 0.314 mm/s.

Fig. 6 shows the 'force output vs clutch voltage curve'. It can be seen that the force output decreases steadily with an increase in voltage, because the torque transmission limit of the clutch is decreasing as the voltage is increasing. The maximum tested force output of the actuator is 112 N at a clutch voltage of 0 V.

B. Static Balance and Backdrivability Test

In this experiment we evaluate the static balancing of the actuator and the force required to backdrive the actuator. The actuator was loaded with the maximum payload, i.e. 3 kg, and then it was brought in a static balance by slipping the clutch. The total moving mass that has to be balanced is the payload plus the mass of the vertically moving parts of the actuator, which is about 0.5 kg. The clutch voltage was set accordingly. We tested the backdrivability of the actuator by moving it up and down and got the time curve of the force required to backdrive it. The motor slipped the clutch with an input speed of 1500 rpm. We then slowly moved the output side of the actuator up and down. The force required to backdrive the actuator is so small that even with a 3 kg payload on it, it can be moved upwards with a

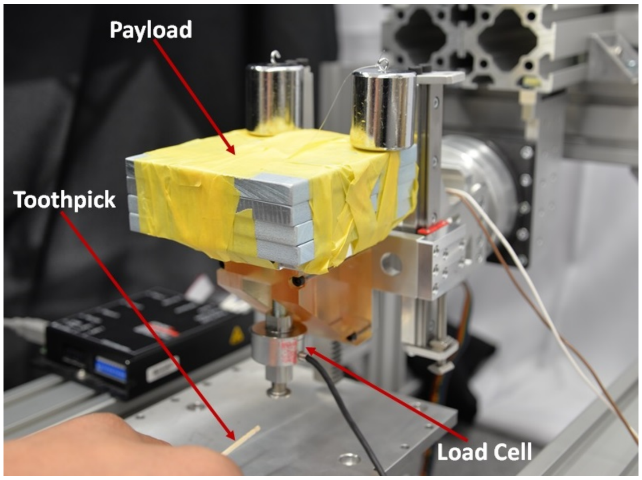

Fig. 7. Backdrivability and static balancing test

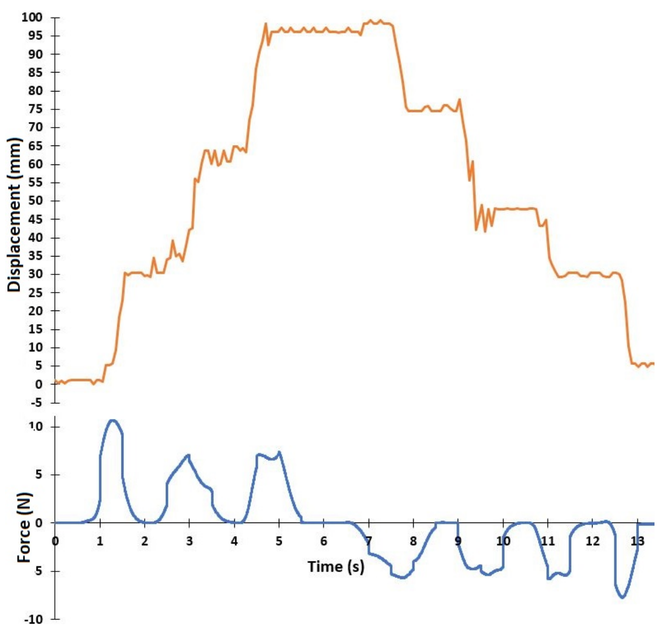

Fig. 8. Backdrivability Force. The top figure shows the displacement of the actuator in mm, the bottom figure shows the backdrivability force, when the actuator is loaded with 3 kg payload. The weight of the moving parts of the actuator without the payload is approximately 0.5 kg.

toothpick, without breaking the toothpick. For measuring the force required, we actually used a toothpick to move it up, as shown in Fig. 7. To move it downwards, we grabbed the bottom part of the load cell tightly and pulled it downwards in order to get the force data from the load cell. We did not move the actuator continuously during the testing to check if it remains in static balance whenever the force is removed.

Fig. 8 shows the force required to backdrive the actuator and the resulting displacement. As the encoder on the output side of the clutch was not functional at the time of the experiments, the displacement was measured with an ultrasonic sensor, which adds some imprecision to the measurements. Peaks and valleys in the force measurements correspond to upward and downward movements, respectively. The system has some friction, for example from the linear guides, which needs to be overcome when moving the payload. Forces of around 5-10 N need to be applied to move the output in both directions, which is a force that an average human can comfortably exert. Furthermore, when no (or too little) force is applied, the output remains stationary, which proves that static balancing was successfully implemented.

We performed the same experiment with a 2kg payload (using a corresponding clutch setting), and the same range of forces was needed to backdrive the actuator, demonstrating that the force necessary to backdrive the actuator is largely independent from the payload. However, we expect that the friction in the system could change according to the payload. Moreover, the force necessary to accelerate the payload depends on its mass.

C. Impact Test

We measured the impact force of the actuator with this test. The goal was to check if it is in compliance with ISO-TS 15066 standards. With the exception of the face, the impact force should be less than 110N according to the ISO-TS 15066.

We put the maximum payload on the actuator, i.e. 3 kg and rammed the actuator against a rigid surface. Fig. 9 shows the force that the actuator applies when the clutch is either set to being stiff or when the clutch is set to being backdrivable, i.e. the clutch was set to holding 30N, which together with the friction in the system was just enough to hold the payload. The speed of the motor was set to 2000 rpm, because at higher speeds the motor shut down due to overcurrent at the time of the impact with the stiff clutch setting.

At the moment of impact, because the actuator cannot move any further, the clutch starts to slip to produce a downward thrust. In addition, 35N downwards are being produced by the weight of the payload and the actuator. In the case of the backdrivable clutch setting, in total about 65N were applied, while with the stiffer setting 133N were applied.

It can be seen from Fig. 9 that the force takes about 0.3s to build up. This could be due to the backlash between the rack and pinion, elasticity in the system, or the clutch, or a combination of these factors, and will be further investigated in future work.

We performed the same experiment with the compliant clutch setting at the maximum motor speed of 3000 rpm (corresponding to 94 mm/s), and the resulting force graph looked nearly identical.

D. Quantification of Backdrivability

Few metrics exist to quantify backdrivability. We took inspiration from the 'Impact Mitigation Factor (IMF)' [19]. It quantifies how bad the impulse would be for same impact velocity and same payload, if the joint was not backdrivable. IMF can be calculated by comparing the impulse of the actuator at maximum velocity and payload when it is stiff, with the impulse of the actuator in the same conditions, except it is backdrivable. If I is the impulse of the actuator

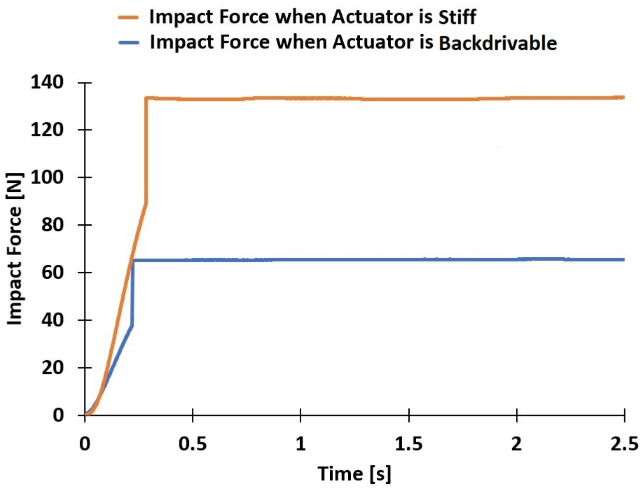

Fig. 9. Impact Force, when actuator is loaded with 3 kg payload and made to travel its complete stroke when it is stiff or backdrivable, respectively.

when it is stiff, and I_b is the impulse when the actuator is backdrivable, the IMF can be calculated as follows [19]:

$$IMF = \frac{I - I_b}{I} \quad (1)$$

The IMF lies between 0 to 1. An IMF corresponding to 1 indicates a perfectly backdrivable system, whereas $IMF \rightarrow 0$ indicates that system is stiff, as $I_b \rightarrow I$. Basically, the lower the IMF, the stiffer the system.

In the case of our proposed actuator design, we are interested in comparing the maximum forces that occur when the actuator is backdrivable or stiff, respectively, and want to analyze what fraction of the maximum impact was mitigated. Therefore, we replace I and I_b in equation (1) to be the maximum forces in the stiff and backdrivable condition, respectively. Using the data from Fig. 9, we can calculate that the actuator is capable of mitigating about 51.1% of the force.

E. Power Consumption Test

Power consumption is very important in industrial machinery, as it directly affects the revenues of an industry. In case of the proposed design, there are two elements that consume power, one being the motor and the other being the clutch. An experiment was performed to assess the power consumption of the actuator.

During this experiment, we assumed a drilling operation with a steady feed of 300 mm/min and calculated a power consumption against force output curve. The pitch-line velocity of a pinion is calculated as $V = \pi d_p N/60$, where V is the pitch line velocity of the pinion, which in turn, is the output speed of the linear actuator, d_p is the pitch circle diameter of the pinion and N is the speed of the pinion in rpm.

The power consumed by the clutch and the power consumed by the motor were measured separately and the total power consumption was calculated.

The power consumed by the clutch is calculated as -

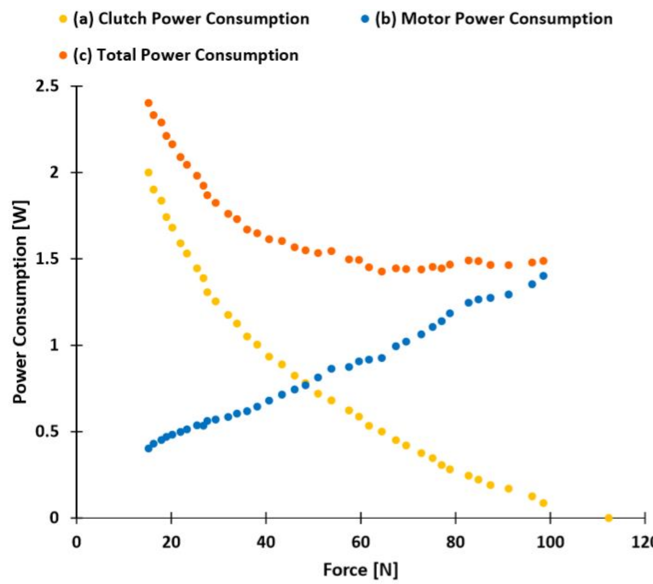

Fig. 10. Power consumption of the actuator. The yellow curve corresponds to the clutch power consumption; the blue curve corresponds to the motor power consumption and the orange curve corresponds to the total power consumption of the actuator.

$$Clutch\ Power = \frac{(clutch\ Voltage)^2}{Coil\ Resistance} \quad (2)$$

The clutch voltage is variable, while the coil resistance of the clutch is constant at 288 Ω. The yellow curve in Fig. 10 shows the clutch power vs force output curve. Since the clutch shows maximum disengagement at maximum input voltage, that is 24 volts, the actuator consumes maximum clutch power, when it produces minimum output force. The maximum power consumed by the clutch is 2 W. At 0 V, obviously no power is consumed by the clutch, but the actuator force output is maximum.

The power consumed by the motor is calculated as -

$$Power\ consumed\ by\ the\ motor\ = \\ motor\ voltage\ \times current\ consumption \quad (3)$$

The blue curve in Fig. 10 shows the motor power consumption against the force output curve. The power consumption increases linearly with force output. The maximum power consumed by the motor is 1.4 W.

The total power consumed by the mechanism is simply the sum of the power consumptions of the clutch and the motor for the respective force outputs. The orange curve in Fig. 10 shows the total power consumed vs. force output curve. The maximum power consumption is 2.4 W, at the speed of 5 mm/s.

An important point to note here is that this power is calculated for a velocity of 5 mm/s which is one of the standard feeds for drilling, as mentioned earlier. As the velocity of the actuator increases, the power consumption will increase. We examined the maximum power that this mechanism consumes. The actuator consumes maximum power when it is run at the maximum speed (94 mm/s) and there is maximum disengagement of the clutch (24 V). The maximum power consumed by the actuator is 11.31 W.

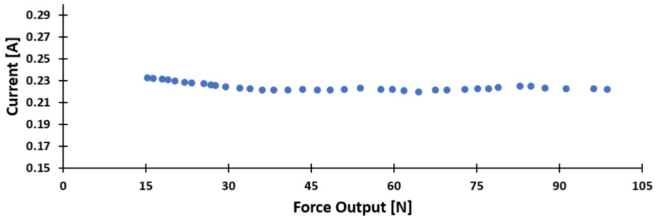

Fig. 11. Current consumption vs force output. The current consumption of the actuator is almost constant with respect to the force output.

We also observed that the current consumption of the actuator changes very little with the output force. This is due to the fact that the current consumption of the clutch decreases with an increase in the force output, and the current consumption of the motor increases with an increase in the force output. Fig. 11 shows the current consumption vs force output curve.

VII. CONCLUSION AND FUTUREWORK

We presented an implementation of a linear series clutch actuator. Even though series clutch actuators have been proposed and implemented before, the scope has been limited to rotary actuation. This paper presents the first implementation and evaluation of a vertically oriented linear series clutch actuator. The mechanical system was explained. We used a simple rack and pinion mechanism to obtain linear movement out of otherwise rotary actuator. We also presented a method for achieving backdrivability and static balancing with the clutch.

We evaluated the linear actuator for force output, backdrivability, static balancing, impact force and power consumption. The actuator can produce a maximum of 112N force, and easily achieves the payload capacity of 3kg that we aimed for. It is comfortably backdrivable, and we also demonstrated that the moving mass of the actuator and the payload could be statically balanced by slipping the clutch. The force required for backdriving the system is about 5-10 N, irrespective of the payload. Finally, the actuator consumes maximally 11.3 W power.

The current implementation is a first prototype, and there is room for improvement. Many parts in this design can be optimized, for example the selection of the harmonic drive can be optimized. Finally, we aim to implement this actuator in a 3-axis robot.

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