**Invited Paper**

**Work in the Time of Covid-19: Actuators and Sensors for Rehabilitation Robotics**

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This paper reports on our work conducted during 2020 in the development of actuation and sensing techniques and devices. In gait rehabilitation, active body weight support systems are often needed to guarantee the safety of patients. These support systems are required to operate at two distinct operation points: a high-force operating mode to hold a patient and prevent falls and, conversely, a “transparent mode” that reduces the mechanical impedance of high-force actuators to enable patients, even those who are weak or paralyzed, to easily express movement. However, the ability to deliver high forces and easily manipulate robots is a key challenge in improving the force-based interaction control. Force feedback is an effective approach to reduce the inertia and friction of robots, but stability is paramount particularly when interacting with humans. By modeling the environment as a second-order spring-mass-damper system and considering the phase response, we derived the control parameter gains required to guarantee a stable human-robot interaction. The design of actuators with intrinsically adjustable mechanical properties is a complementary strategy. For instance, the stiffness of actuators can be modulated by adjusting the unsupported length of a cantilever leaf spring. To model the spring stiffness under deflection, an ideal cantilever support model cannot be assumed for a conventional design of a slider with dual roller pairs, particularly with a soft spring. We proposed a beam deflection model considering the non-zero slopes at the contact points between the rollers and spring. The spring parameters were determined to attain the desired range of stiffness with a short traveling distance of the adjuster. For a single degree-of-freedom (DOF) linear motion, we investigated a macro-mini actuation concept using an electrorheological-fluid brake. Balancing these conflicting requirements between the driving force generated from the non-backdrivable high-force unit and the low-inertia and low-friction unit was achieved by controlling the electrical field affecting the fluid yield stress between the rotor and stator electrodes of the brake. One of the limitations of the feedback control scheme was noisy force sensors. We discuss our novel proximity and force sensor using optical techniques and conclude with a description of low-profile 3-DOF flat motor.

**Keywords**: Rehabilitation robotics, body-weight support system, variable stiffness actuator, planar motor, tactile sensor

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1. **Introduction**

Robots have been proven effective throughout several decades in structured environments, for example, populating a circuit board or spray painting the frame of a car. To become more pervasive in society, modern robots are required to work in unstructured environments and, in some cases, in close contact with humans. In such cases, they not only need to detect the users’ intention but they must also respond appropriately to humans guaranteeing both stability and adequate task performance. We pioneered the field of robot-assisted therapy in 1989 when we started the development of what became known as the MIT-Manus robotic gym [1]-[6]. Robotics may offer an opportunity to promote the amount of motor practice needed to “relearn” motor skills lost due to a stroke while potentially reducing therapist participation [7]-[11]. To tailor therapy to the particular patient’s need, robot-assisted therapy requires different modes of operation, namely: passive, active, resistive, or assist-as-needed [6, 12, 13]. For example, patients might need assistance in initiating or completing movements, guidance during movement, and in other cases they might benefit from resistance to motion, or even the ability to freely express weak or paralyzed movement during evaluations [14]-[16]. In a nutshell, we must guarantee robustness against dynamic uncertainties and variable interactivity to enable highly responsive guidance or assistance. For the most part, this was attained by designing highly backdrivable robotic devices with intrinsic low mechanical impedance as in the MIT-Manus robotic gym for the upper extremity. But in some situations, this is not attainable. For example, in a robotic body-weight support system (BWS) high force, high mechanical impedance is needed when the robot must prevent a fall or, on the contrary, when high backdrivability and lower mechanical impedance is a “must,” when the robot must get out of the way to allow frail patients to express their attempts to walk independently [5, 17].

In this case, proper modulation of the mechanical impedance is a key feature of successful physical human–robot interaction (pHRI) and there are two complementary strategies: feedback control and physical modification of the actuator properties [18]. These are particularly important when designs with low-mechanical impedance coupled with low-force output are out of the question, as in the case of BWS. High performance BWS systems, with agile control of interaction force between a human and a robot, is facilitated by control and modulation of the
mechanical impedance. High transmission ratios and their associated intrinsic properties (friction and reflected inertia) for high-force actuators impede the effective design of low mechanical impedance required in some situations. Feedback control and the intrinsic variation of mechanical impedance might afford a better tradeoff towards getting low mechanical impedance when needed on high-force actuators, which is an important challenge to improve the force-based interaction control of such systems dealing with limited knowledge of environmental dynamics.

This paper reports our efforts on developing actuation and the sensing techniques which can be applied in some rehabilitation robots with special requirements. Force feedback is an effective way to reduce robots’ inertia and friction, but stability is paramount especially when interacting with humans. By modeling the environment as a second-order spring-mass-damper system and considering the phase response, we derived the control parameter gains required to guarantee a stable human-robot interaction [18]. An alternative to feedback control is to design actuators with intrinsically adjustable mechanical properties. In this complementary strategy, the stiffness of actuators can be modulated by adjusting the unsupported length of a cantilever leaf spring. To model the spring stiffness under deflection, the ideal cantilever support model cannot be assumed for a conventional design of dual roller-pairs slider, particularly with a soft spring. We presented a beam deflection model considering the non-zero slopes at the contact points between the rollers and the spring [19]. The spring parameters were determined to attain the desired range of stiffness with a short traveling distance of the adjuster. We also explored an alternative for a single-degree-of-freedom BWS in the form of a macro-mini actuation concept using an electrorheological (ER)-fluid brake. Allocation between the driving force generated from the non-backdrivable high-force unit and the low-inertia unit was achieved by controlling the electrical field and consequentially the fluid yield stress between the brake’s rotor and stator electrodes. High force and high backdriveable actuators require “quality” sensing for the feedback control or to adjust the intrinsically adjustable mechanical properties. We developed a tactile sensing technique using optical range sensors in combination with a transparent elastic sheet to provide both range and also the contact force estimation [20]. This sensor might be particularly useful in assistive technology. For example, in a mobile robot used to fetch objects for a bedridden person. So far, we described our efforts on developing high force backdriveable actuators for a robotic body-weighted support system (BWS) and sensors to grasp objects. We will conclude discussing efforts on the low force, highly backdriveable actuator with a low profile that could possibly be employed in a home robot.

This paper is organized as follows: Section-2 describes the derivation of the parameter gains to guarantee the control stability. Section-3 presents the adjustable unsupported-length leaf spring mechanism along with the beam deflection model considering the non-zero slopes at the contact points. Section-4 introduces the macro-mini actuation concept using ER-fluid brake to connect the high-force and the low-inertia modules. Section-5 discusses the novel proximity and contact force sensor. Section-6 presents our investigation on the low-profile 3-DOF flat motor designed for upper extremity rehabilitation, while Section-7 summarizes the key findings and the on-going efforts.

2. Stability of Force Feedback Control

BWS robots have two extremely different operating points: a) highly backdriveable (low force) operating condition and b) high output force condition. BWS robots must be able to easily ‘get out of the way’ to allow patients to express unencumbered movements when they can, but they are also required to provide high mechanical impedance and assistance when a patient needs it. This section explains how we achieved the desired property via feedback control.

![Fig. 1. The experimental setup reproduces the existing BWS system which consists of a leadscrew system driven by a rotary motor with a force transducer mounted to the nut bracket of the lead screw.](image)

![Fig. 2. Control block diagram.](image)

2.1 Hardware and Control Structure

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Fig. 1 shows the hardware used in this study. The hardware was designed to be as simple as possible so that our proposed controller can be applied to various actuators and it resembles the configuration of existing BWS systems. The lead screw reduces the mechanical backdrivability that has the equivalent role of a gear. Since the objective is to derive a controller that is applicable to a wide variety of hardware, we assumed the hardware to be modeled as a second-order system and we confirmed experimentally that the hardware didn’t have any significant resonance in our control bandwidth by running the frequency response test.

Fig. 2 shows our control block diagram including the human model [18]. The control structure uses a force feedback gain and a phase-lag compensator, respectively. The main reason for using the phase-lag compensator was to have high force feedback gain at low frequency where static friction force is dominant. In a nutshell, the added zero can cancel the original mechanical pole, and the added pole becomes the dominant one improving backdrivability of the actuator. From a classic control theory point of view, the original mechanical pole must be “replaced” by a new dominant one so that the mechanical friction effect can be attenuated. The combination of this new dominant pole and zero to cancel the original mechanical pole constitutes the phase-lag compensator.

The virtual stiffness $K$ and damper $B$ determine the impedance of the endpoint. $K$ and $B$ should be pre-determined regardless of the stability condition. Therefore, there is a total of three control parameters (force feedback gain, pole and zero of phase-lag compensator) requiring tuning.

Stabilizing the human robot interaction requires the dynamics of the human model. For the simplicity and wide applicability, we used the following second order model:

$$Q(s) = m_H s^2 + b_H s + k_H$$

where $m_H$, $b_H$, $k_H$ stand for the inertia, viscosity, and the stiffness of human, respectively. The phase response of the human model is bounded as

$$0^\circ \leq \angle Q(s) \leq 180^\circ$$

since only the order is assumed. It is difficult to anticipate the stiffness or inertia for any environment unless the characteristics are known in advance. It is easier to focus exclusively on the phase response because equation (1) is true for all the environment represented by a mass-spring-damper model. Further detail will be included in [21].

### 2.2 Coupled Stability

By focusing on the human robot interaction, Fig. 2 can be further simplified as shown in Fig. 3. The structure itself is simple, but the block diagram elegantly expresses the physical meaning of what the interaction is. When a robot and human are in contact and interacting with each other, the direction of the applied forces are in opposite directions (represented in the block diagram as -1). Conversely, the two will move in the same direction when the two are coupled. To maintain the stability of this closed loop, the transfer function of the robot impedance must be properly designed. Otherwise, we cannot guarantee the robot to have contact with any kind of environment that is modeled as eq. (1).

The open loop transfer function of the block diagram $H(s)$ is useful to examine the stability of the closed loop system, which is

$$H(s) = P(s)Q(s)$$

The phase response of $H(s)$ is the angle between the real axis and the vector pointing at a specific coordinate of the transfer function in the s-plane. In other words, the response can be graphically displayed in the complex plane. When phase response of $H(s)$ does not cross $-180^\circ$ at any frequency, the gain margin will be $\infty$ dB and the phase margin will always be guaranteed, which means that the system is asymptotically stable. Therefore, the control parameters in Fig. 2 must be designed so that $\angle H(s)$ is greater than $-180^\circ$ at any $\omega$. Regardless of the magnitude of $Q(s)$, we are able to bound the stability margin. For example, even if the environment is stiff, this margin guarantees that the interaction is stable.

The summation of the phase response of $P(s)$ and that of $Q(s)$ will be the phase response for the whole transfer function represented by equation (2), namely:

$$\angle H(j\omega) = \angle P(j\omega) + \angle Q(j\omega)$$

The phase response range of $Q(s)$ is bounded as shown in equation (2). Therefore, the requirement for the robot transfer function $P(s)$ can be expressed as follows:

$$\forall \omega \geq 0; \quad -180^\circ \leq \angle P(j\omega) \leq 0^\circ$$
To fulfill this condition, the function must not cross the real axis of the complex plane at any frequency. If the function is within the third or fourth quadrant of the complex plane, the system maintains a stable contact with any second order environment. It also can be viewed as the appropriate placement problem of the pole and zero to constrain the phase response within equation (5) range. As we mentioned previously, the pole of the phase-lag compensator becomes the dominant pole, which enhances the backdrivability by reducing the apparent viscosity. The zero of the compensator keeps the balance to satisfy equation (5). Since the only assumption of the environment model is expressed by eq. (2), this method can be applied to a range of environments.

The physical meaning of the condition expressed in equation (5) can be better comprehended when considering extreme cases. As pointed out in [22], the worst cases occur when the environment is conservative (e.g., either a pure spring or mass with no friction). When a robot whose phase response crosses $-180^\circ$ contacts with a stiff spring, it may jeopardize the phase margin of $H(s)$ in the high frequency region because the high gain that the spring has can push the point where it crosses $-180^\circ$ to the left of $(-1,0)$ in the complex plane. The contact with a heavy environment may also lose the phase margin in the low frequency region if the phase response of $P(s)$ crosses $0^\circ$ for the same reason. Those elements are lossless environments, meaning that the energy stored in the environment will come back. We had previously described a set of contact experiments with pure mass or spring (for details see [18]).

### 2.3 Improvement on Backdrivability

We can examine whether the system backdrivability has improved or not by measuring several indices such as static friction force, apparent inertia and viscosity of the controlled hardware. First, a simple experiment allows us to measure the equivalent static friction force from the position versus force plot when commanding the virtual spring behavior in the impedance controller and slowly moving the system back-and-forward at constant speed. The difference between the forward and backward motion represents the static friction force. The smaller the gap, the higher the system backdrivability becomes.

Fig. 4 shows the results of how low the static friction force becomes with higher force feedback gain. The red dots represent the result of our proposed controller, while the blue dots are a simple force feedback behavior of existing commercial systems without the use of the phase-lag compensator. The controller without the phase-lag compensator cannot enlarge the force feedback gain further because the noise from a force transducer is also amplified. On the other hand, our proposed controller was able to operate at much higher gain. The result showed that the phase-lag compensator lowers the force feedback gain in the high frequency. We can interpret the physical meaning of adding the phase compensator as modifying the inertia at different frequencies. The actuator became “lighter” at lower frequency region and “gained” weight at the higher frequency range. We confirmed that our controller was able to reduce the force needed to overcome static friction more than 6,000 times.

A step response test was used to obtain the apparent inertia and viscosity of the controlled hardware. Fitting the response to a second order model system allows us to estimate the values. The results are shown in Fig. 5. Similar to Fig. 4, the leftmost dot is the original mechanical parameter. The increase of the force feedback gain reduces both indices. Apparent inertia became about 14 times smaller than the original one, while the viscosity was reduced about 12 times. Although the amount of the reduction is quite significant, the noise of the force transducer prevented us from setting even higher gains. A more noiseless sensor will enable us to make the system even more backdrivable. A manuscript describing the complete procedure of selecting the controller parameters to guarantee stable human robot interaction and high backdrivable performance is in preparation.

### 3. Variable Stiffness Leaf Spring Mechanism

#### 3.1 Adjustable Unsupported-Length Leaf Spring Model

Taking advantage of the nonlinear behavior of an energy storage element to provide a broad range of stiffness values, we applied the concept of adjustable unsupported-length leaf spring for stiffness modulation of the force-based interaction control in one translational DOF (see Fig. 6) [19]. The small-deflection leaf spring mechanism was integrated with a non-backdrivable equilibrium-position adjuster. Our proposed strategy only requires a linear position sensor for measuring the spring deflection at the endpoint. To transmit the load from the interaction force through the elastic component directly to the supporting structure of the roller-slider support, this type of actuator requires low power to adjust and maintain a desired stiffness. A high stiffness can be achieved by moving the roller support close to the endpoint.

Cantilever leaf-spring mechanisms with adjustable unsupported length were applied, for example, to the fingertip of a grasping system [23] or for stiffness augmentation in an ankle-foot prosthesis [24]. They were also employed to provide a constant joint stiffness against their angular displacement in the joint driving unit of a robot arm [25]. Broad ranges of stiffness modulation were achieved consuming little energy [26] – [28].

The support positions of the leaf spring were adjusted by a planetary gear system [29], by controlling the relative rotation between two actuators [30] or by using the screw-slider-linkage mechanism [31]. An actuator was designed for stiffness augmentation instead of driving a joint [32]. Intelligent stiffness augmentation can play a significant role in passive exoskeletons for walking [33][34], running [35], and cycling [36].

#### 3.2 Stiffness Model Considering Non-Zero Slopes of Dual Roller-Pairs Support

Nonlinear models for accurate stiffness estimation of a large-deflection beam were previously presented in [37][38]. The low-complexity methods, such as the pseudo-rigid-body model and the simple stiffness equation [39] based on the elliptic integration solution (EIS) [40], were also proposed. While not employed in most rotational applications, the basic beam deflection model, as the equivalent static friction force from the position versus force plot when commanding the virtual spring behavior in the impedance controller and slowly moving the system back-and-forward at constant speed. The difference between the forward and backward motion represents the static friction force. The smaller the gap, the higher the system backdrivability becomes.

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used for designing the planar spiral spring of the parallel elastic actuator [41], was applied to our linear variable-stiffness mechanism (LVSM) which maintains the small endpoint deflection by using the vertical equilibrium adjuster [19].

A conventional design of dual roller-pairs slider for adjusting the unsupported length cannot be assumed as an ideal cantilever support, especially with a soft spring and when the distance between the pairs of rollers is significant (see Fig. 6.). Based on the general linear Euler-Bernoulli beam equation, we derived the stiffness model considering the non-zero slopes at the contact points between the rollers and the spring.

\[
P(\epsilon) = \frac{6EI}{l_0^3 + \frac{3}{2}l_0 l_x^2 - l_o^3 - l_0^2 l_x - \frac{1}{2}l_0^2 l_x^2 - \frac{1}{3}l_0^3 l_x^3 + \frac{1}{6}l_0^5} \quad (6)
\]

The stiffness at the applied force’s position \(x = l_0 + l_x\), which is the ratio of the force \(P\) over the magnitude of the deflection \(\epsilon(x)\), is written in terms of the modulus of elasticity \(E\), the second moment of area about the spring’s neutral axis \(I\), the horizontal offset \(l_o\) between the rollers, and the deflected length of spring \(l_x\).

\[
\epsilon(x) = \frac{y(x)}{l_0} = \frac{P}{6EI}(x - l_0)^2 - \frac{P}{2EI}(x - l_0) + \frac{P}{3EI}
\]

In the experiment, the stiffness adjuster was settled at seven different positions corresponding to the spring’s deflected length between 12 and 90 mm. At each position, the endpoint deflection was gradually adjusted by the motion of the equilibrium-position adjuster. The endpoint force was also recorded. The stiffness values at different deflected lengths of the 0.5-inch-width AISI-1075 spring strips (with 0.028-inch and 0.062-inch thicknesses) are plotted in Fig. 8. The estimation using the basic beam deflection model is shown by the dashed lines as a baseline for comparison. For each spring, our improved model considering the non-zero slopes at the supporting points of the stiffness adjuster provides a significantly better estimation, especially in the high stiffness region with large bending of the springs.

3.3 Deflected Length–Stiffness Relationship

The alpha-prototype of the adjustable unsupported-length leaf spring mechanism for stiffness modulation was installed on a vertical lead screw system shown in Fig. 7. The spring is fixed at the left end, whereas the external force is applied on the deflectable right end. A linear encoder is used for measuring the endpoint deflection. The stiffness adjuster, having two pairs of urethane rollers, was designed to travel along the length of the spring strip. The horizontal driving unit uses a precision ball screw actuated by a high-speed DC motor, along with a parallel pair of linear bearings. The motor allows the completion of the full range stiffness modulation (90 mm traveling distance) within 0.088 sec.

4. Macro-Mini Linear Actuator Using ER-Brake

4.1 ER-Fluid and MR-Fluid Actuators

Electro-rheological (ER) fluids and magneto-rheological (MR) fluids are colloids, i.e., the suspension of nonconducting micro-particles contained in an insulating carrier fluid. The particles form chains along the direction of the externally applied field (electric field for ER fluids or magnetic field for MR fluids) and the columns resist shearing of the fluid perpendicular to the field. As the apparent yield stress of the fluids can be controlled by the intensity of the applied field with the response time in the order of a millisecond, ER and MR-fluids were applied in several quasi-passive mechanical devices such as clutches, brakes, dampers, and valves [42]. ER-fluids have the advantage of fast response time, low system inertia, and low current density, and they were previously applied in upper-extremity rehabilitation robots [43], active orthotics for knee rehabilitation [44], strength training machines [45], and MRI-compatible hand rehabilitation system [46]. However, the commercial adoption of ER fluids was limited over the past two decades because of important handicaps including low yield stress, limited temperature range, particle sedimentation and levitation [47]. The haptic interface devices [48][49] using MR fluids with high yield stress are more stable, transparent, compact size, low mass-torque, and inertia-torque ratios, with intrinsic passivity and precision controllability. The theoretical torque and inertia of MR-fluid clutches were derived for the multiple-discs design [50] and the long-cylinder design [51]. Antagonistic actuation of multiple joints can be obtained from a single unidirectional motor located remotely from the joints by using MR-fluid clutches [52]. Asahi Kasei (Tokyo,
Japan) had developed a new prototype of ER fluid designed to address some of the issues mentioned earlier. Our group re-examined the potential of using their novel ER fluid through systematic analysis of smart materials for rehabilitation applications. By varying the strength of the field applied on the ER-fluid brake [53], the system’s stiffness and damping could be controlled. The ER-fluid clutches were antagonistically arranged in a differential-gear mechanism [54][55] to decouple the output from the intrinsically high impedance of a geared DC motor.

4.2 Macro-Mini Linear Actuator
We developed a linear actuator alternative using a rotary ER-fluid brake to connect the highly backdrivable unit with the high force, high transmission ratio unit as shown in Fig. 9. For low-impedance interaction, the endpoint is driven by a low-inertia motor through the Roh’Lix transmission which is also connected to the brake’s rotor. The brake’s stator is mounted on the nut bracket of the high-force actuator. Rotation in the brake allows the translation between the endpoint and the high-force actuator. The mechanical impedance can be modulated by controlling the fluid friction in the brake through the voltage applied on the rotor and stator electrodes.

The impedance is fully controlled by the high-force actuator if the brake is completely locked, while conversely the extremely low impedance is obtained with the deactivated brake. This drivetrain configuration not only allows the rapid switching between the low and the high impedance modes, but also holds the patient in case of tripping or falling. In the undesired circumstances when the low-inertia actuator cannot provide enough support force for a sudden load change, the endpoint will just move down to the bottom limit. The concept is very promising for the active body weight support systems requiring high force against gravity. In terms of energy consumption, the ER-fluid brake concept only dissipates the energy when the relative displacement occurs whereas the other techniques using ER-fluid clutch always consume the energy by continuously rotating the velocity source.

The custom design of ER-fluid brake using separable concentric cylinders and shown in Fig. 9 has a small radius difference between the adjacent parts, which can provide a high torque-to-inertia ratio. Our prototype of ER-fluid brake was experimentally characterized, and the results are shown in Fig. 10.

5. Optical Sensor Capable of Measuring Distance, Tilt, and Contact Force
As discussed earlier, the feedback control scheme developed for high force, high backdrivable actuators depends on the quality of the force sensor. Indeed, we demonstrated that a less noisy sensor will enable us to make the high force actuator behave in an even more backdrivable manner [18]. The characteristics of the entire system can be changed by applying feedback control based on the sensed information [56], [57]. Therefore, we are working on the development of novel sensors to reduce noise and augment flexibility and address some shortcomings of existing sensors.

The measurement principle of the newly developed optical sensor is shown in Fig. 11. The sensor consists of several distance-measuring sensor units, a spring, and a transparent sheet. As shown in Fig. 12, the distance-measuring sensor unit emits infrared light from a light-emitting diode (IR-LED) and it acquires the incident position of the reflected light with a position sensitive detector (PSD). The distance to the object can be measured based on the geometric relationship with the object from the incident position of the reflected light. Since the PSD is configured to derive the incident position from the distribution of the incident light intensity, the distance information to the object can be obtained with little influence from the reflectance of the object or the ambient light. This sensor can measure the distance when the object is located farther than the equilibrium length of the spring. On the other hand, if the object is located closer than the equilibrium length of the spring, the sensor acts as a force sensor. Fig. 13 shows the alpha-prototype sensor employed during testing. The transparent sheet was mounted on the prototype via two springs. The four units (Sharp Corporation, GP2Y0A21SK0F) mounted at each vertex of the rectangle measure distance, tilt, and contact force. Note a fifth unit (Sharp Corporation, GP2Y0A51SK0F) located at the center of the rectangle. This extra unit has the ancillary role of detecting the presence of an object within a larger range. The voltage response and corresponding applied force is shown in Fig. 14. This voltage response is the
average of the output voltages of the four sensors attached to each vertex. Note that proper calibration is needed to take into account the stiffness of the used springs. For more details see our recently published papers [20][58].

The incident position of the reflected light changes depending on the distance to the object.

Fig. 12. Measurement of distance based on geometric relationships.

6. Low-profile 3-DOF Flat Motor

The MIT-Manus shoulder-and-elbow robot is an end-effector type robot that employs two direct drive motors mounted co-

Fig. 14. Voltage response and applied force.

Fig. 15. Structure of 3-DOF low-profile flat actuator.

Fig. 16. 3-DOF low-profile planar movement (arrows in the figure indicate the direction of movement and the numbers indicate chronological order of the commands).
An overview of our alpha-prototype of the active 3-DOF flat actuator is shown in Fig 15. Permanent magnets are attached to the mover, and by controlling the excitation pattern of the coils on the stator side, we can control a 2-DOF horizontal and 1-DOF rotational motion. Figure 16 shows how this actuator operates. By designing the excitation pattern of the coils, it is possible to realize a complex motion that combines horizontal and rotational motions as shown in Fig. 16. The experimental results of the rotating motion of panel 6 in composite Fig. 16 is shown in Fig. 17. In this experiment, we suddenly switched the position of the energized electromagnets and the response converges in 0.2 seconds. We expect a better response when applying feedback control and gradually switching the duty ratio of the energized electromagnets.

7. Conclusions

This paper summarizes our efforts on the design of novel actuators and sensors intended for pHRI, but are also applicable to robotics in general. We discussed two complementary strategies to implement high-force high-backdrivability actuators that guarantee stability and achievable performance: feedback control and physical modification of the actuator properties. We also discussed limitations on the feedback control scheme due to noisy force sensors as well as our design of an alternative sensor that could address this deficiency as well as other important deficiencies of existing proximity and force sensors. We concluded discussing a novel low-profile motor design that eliminates the need of quality force sensor for when low force and inherently high backdrivability is a potentially good solution.

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