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Differential-Damper Topologies for Actuators in Rehabilitation Robotics

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Abstract— **Differential-damper (DD) elements can provide a high bandwidth means for decoupling a high inertia, high friction, non-backdrivable actuator from its output and can enable high fidelity force control. In this paper, a port-based decomposition is used to analyze the energetic behavior of such actuators in various physical domains. The general concepts are then applied to a prototype DD actuator for illustration and discussion. It is shown that, within physical bounds, the output torque from a DD actuator can be controlled independently from the input speed. This concept holds the potential to be scaled up and integrated in a compact and lightweight package powerful enough for incorporation with a portable lower limb orthotic or prosthetic device.**

I. Introduction

Wearable robotic devices for human rehabilitation applications such as therapy and long-term assistance require powerful, safe, and compact actuators that are capable of a wide range of human-scale power output. For optimal biomechanical compatibility, transparency, and safety, such a device must be capable of high fidelity impedance control with low friction and low output inertia [1].

With respect to the hip, knee, and ankle joints, the forces generated by the human musculoskeletal system during activities of daily living generally far exceed the forces which can be generated by e.g. direct-drive electromechanical (EM) actuators due to size/weight restrictions and their limited power density [2], [3]. As a consequence, an EM-based orthotic or prosthetic device that is intended to supplement or supplant these joints will require a transmission with a substantial reduction in velocity in order to fulfill force output requirements. A large transmission ratio will undesirably increase the output inertia, increase drivetrain friction, decrease backdrivability, may introduce backlash and amplified torque-ripple, and will limit the actuator's ability to render high fidelity force control.

To some extent, these issues can be addressed by placing a force sensor at the output and then feeding this signal back to the controller [4]. The system is still, however, inherently subject to high output inertia, feedback gain limitations, and limited controllable bandwidth; all of which act to restrict the overall performance and robustness of the system [5].

A popular approach to this problem is to decouple the actuator from the output through a series elastic element [6]. There are many virtues that are realized with the incorporation of intrinsic compliance, including decoupled actuator inertia, inherent safety and impact robustness, and the promise of efficient storage and recovery of energy [1]. While there exist specific series elastic actuator topologies which can mitigate certain limitations [7], [8], in general they are subject to limited stiffness, limited bandwidth, increased mechanical complexity and redundancy.

The parallel [9] and distributed [10] micro-macro actuator approaches add an additional low power direct-drive motor to a SEA device. The high impedance (macro) motor transmits power through the SEA to the output at low frequencies, while the low impedance (micro) motor improves performance at high frequencies. These methods have been shown to effectively extend the bandwidth of SEA devices at the expense of the added volume, weight, and complexity of the additional componentry.

The actuator may also be decoupled from the output by including an infinitely variable transmission [11], [12]. This approach promises to provide a wide range of achievable impedances with a relatively low energetic cost for control. However, integration of such a device in a lightweight and powerful actuator remains an open issue.

Another method of decoupling the actuator from the output is through the use of a damper or a clutch [13]. Depending on the level of engagement of the damper, the observed output inertia and friction can be reduced; concurrently the backdrivability is increased. As this method is not subject to the upper bound on stiffness imposed by most SEAs, it may be capable of rendering a wider dynamic range of impedances and, due to the energetically dissipative nature of dampers, is inherently stable to control. Also, dampers tend to be volumetrically efficient at generating resistive forces. Additionally, variable dampers can generally be controlled with a high bandwidth. As a negative, dampers lack the inherent shock-absorption robustness and energy storage capabilities of a compliant actuator and also require additional componentry. Note that it would also be conceivable to construct an actuator with both series elasticity and damping.

In order to enable force control using a variable damper, several possibilities exist for where it may be placed. One is to use an inline damper in series between the transmission and the output [14]. Another topology couples the actuator to the damper through a differential gear [15] (thus dubbed a "differential-damper (DD) actuator"). Building upon this, a promising series of dual-differential-damper devices have been developed [16]. Through the use of two differentially coupled magnetorheological (MR) brakes, this design allows for high bandwidth force control with improved bidirectional performance over a single differential design.

While existing DD designs have been demonstrated to be quite effective at rendering forces within the range for which they were designed, no such device has yet been presented

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that is capable of generating the forces that are observed at the human hip, knee, or ankle joints during daily locomotive activities [2]. As it is plausible that this type of design may have certain controllability and energetic advantages over other designs for these joints, it is the objective of this paper to explore the general topology of DD actuators for force control in high power-output joints suitable for incorporation with an active lower limb prosthetic or orthotic device. This will be accomplished through a port-based analysis of differential mechanisms, followed by a conceptual description of DD assemblies, power transmission and efficiency, and through a demonstration using a prototype DD actuator.

II. Port-Based Analysis

A. Port-Based Modeling

For this analysis, it is instructive to point out that differential transmissions can be realized in many physical domains. It is then convenient to use a port-based representation of the actuator [17], in which we account for the total amount of power sourced, stored, and output by the device.

By this method, a system can be decomposed into network of simple interconnected elements, each of which may be represented by a specific set of constitutive equations. The interfaces between these elements are the ports through which power is transmitted. The modularity of this approach allows for component-level analysis of the overall system based on where a control volume cuts these ports. Power can be defined in many physical domains as the product of two power conjugate variables: efforts and flows. Some examples of effort and flow quantities in various physical domains are listed in Table I.

The common effort junction (or 0-junction) is used to connect three-or-more elements which all share the same effort[1]. As this junction is power conservative, the sum of all of the flows directed inward must equal zero, as in Fig. 1a and Eq. (1). By convention, the direction of the half arrow defines the direction of positive power flow, while the causal stroke (the perpendicular bar) indicates the direction in which effort is imposed.

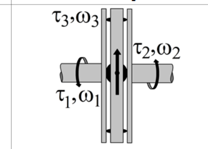
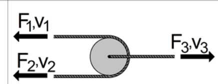
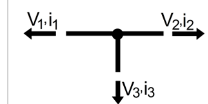
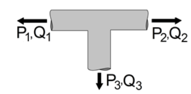
$$e_1 = e_2 = e_3 \ ; \quad f_1 = f_2 + f_3 \qquad (1)$$

B. Differential Analogy

The term "differential" can be used to represent a number of distinct concepts, and so it is necessary to specify the sense in which it is used. Here, a differential mechanism represents a power-conservative three port element in which the sum of the flows directed inward must equal zero, and thus the effort on each port is equal. Hence it is recognized that a differential mechanism – when defined in this way – can be in represented as a 0-junction independently of physical domain.

[1] 2-port 0-junctions are also valid constructs which satisfy the same power continuity constraints. These are necessary when two connected elements have been defined with signs that are not compatible with a single bond.

TABLE I. Some Differential Elements

Domain	Effort	Flow	Differential Example
Mechanical Rotation	Torque, τ [Newton-meter]	Angular Velocity, ω [radian/sec]	 τ_3,ω_3; τ_2,ω_2; τ_1,ω_1; Wheeled Differential Gear
Mechanical Translation	Force, F [Newton]	Velocity, v [meter/sec]	 F_1,v_1; F_3,v_3; F_2,v_2; Pulley
Electrical	Voltage, V [Volt]	Current, i [Ampere]	 V_1,i_1; V_2,i_2; V_3,i_3; Electrical Node
Hydraulic	Pressure, P [Newton/meter^2]	Volumetric Flow Rate, Q [meter^3/sec]	 P_1,Q_1; P_2,Q_2; P_3,Q_3; Pipe Junction

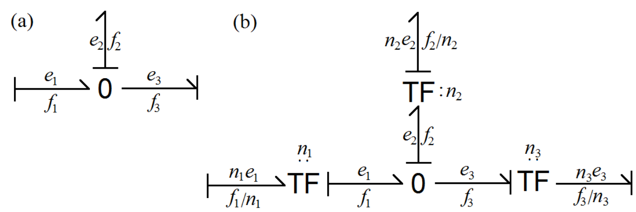


Figure 1. Port-based representation of differential elements, (a) mapped to virtual coordinates (b) expanded to physical coordinates.

It should be noted that this common effort junction appears at the very core of the model of a differential mechanism. That is, the geometric parameters representing the physical design of the component (n_1, n_2, and n_3) can be interpreted as external transformations that are applied prior to connection with the central 0-junction (Fig. 1b). As a physical interpretation, geometric parameters could represent the radii of the gears used in a rotational differential or the cross-sectional areas of the flow channels used in a fluid differential. These transformations need-not be fixed values, as they would not be in the case of a variable transmission [11], [12].

A non-exhaustive list of examples of differential mechanisms in four physical domains is provided in Table I. Again, at the core of each of these elements is a common effort junction. The take-away concept here is that if it is desired to incorporate a differential in the design of a device, that this differential can be implemented in any physical domain. This energetic equivalence means that it is possible that a device can traverse physical domains in order to enable a differential flow output. Such a transformation may be beneficial for leveraging the advantages of physical components in one domain or another.

C. Causality

As was previously mentioned and depicted in Fig. 1a, physical devices are subject to causal constraints. That is, on any bond an element may either accept effort while yielding flow (i.e. act as an admittance), or it may accept a flow while yielding effort (i.e. act as an impedance); no element may simultaneously specify both effort and flow [18].

A common effort junction is causally constrained such that only one of its ports is capable of specifying the effort shared by all other connected ports. From a port-based perspective, it does not matter what physical device is connected in order to generate this effort so long as all bonds at the 0-junction are within the same energetic domain.

For the purpose of the ensuing discussion and of assigning causality, the ports of the 0-junction of Fig. 1a are interpreted as follows:

- Port 1 is the input from the actuator, following any transmission. It is assumed that the actuator-transmission drivetrain appears from a port perspective as a velocity, i.e., flow, source. Hence the effort (causal stroke) is directed back toward the actuator.
- Port 3 is the output port, which ultimately acts through the device on its environment. Convention holds that a physical environment should be regarded as an admittance [18], and so the causal stroke is directed outward on this bond.
- Consequently, port 2 must specify the overall effort observed on the other connected ports. Here, it is possible to connect a second actuator [19] or a second differential [16], but instead it is proposed to connect a semi-active device, e.g., a variable damper.

III. Differential-Damper Topologies

A. Dampers and Semi-Active Devices

In the following, the term *damper* is used to represent a *controlled variable damper*: a semi-active device that can modulate the relationship between its input flow and output effort. An ideal damper is able to continuously modulate its impedance properties from zero (i.e. fully transparent, zero-inertia) to infinite (i.e. completely rigid) with infinite control bandwidth.

Some physical examples of (non-ideal) dampers include magnetic particle [15], magnetorheological [16], electrorheological fluid brakes [20], and eddy-current viscous couplers [21] in both the mechanical rotation and translation domains, variable orifice valves [22] in the hydraulic domain, and transistors [23] in the electrical domain.

It was mentioned above that in order to control the effort imposed by port 2 of a differential mechanism, a second actuator may be connected there. The addition of a second actuator, however, is likely not a good solution for most applications because 1) of the increased power consumption, weight, and volume required for torque generation using an actuator versus a damper, and 2) if the full range (transparent through rigid) of impedance modulation is required, the second actuator would need to generate forces at least equal to the forces generated by the first actuator. This most-certainly would not improve force controllability; the same is the case for inertia and inherent friction.

To reiterate, the chief advantages and motivation for the DD approach come from the ability to decouple the output from the actuator at high bandwidth with relatively low mass and power requirements[2]. So long as the damping provided by the damper can be effectively controlled, the output effort through the differential will also be controlled.

B. Component Selection and Design

In practice, all dampers are subject to physical limitations. For example, the maximum transparency of a mechanical damper is limited by its inherent friction and inertia. The design of a hydraulic valve may create a nonlinear flow-resistance relationship that is difficult to control. The bandwidth with which the damping can be modulated in all domains is always limited.

It should also be noted that variable dampers in some domains may enjoy some advantages over other domains. For example, it is difficult to remotely locate a mechanical damper due to the constraints of mechanical power transmission. A hydraulic damper, however, is easier to relocate thanks to the flexibility of hydraulic lines. Though impressive new designs for mechanical dampers have been demonstrated [24], hydraulic dampers tend to be more adept at harnessing high force levels in a more compact package than their mechanical equivalent.

These trade-offs, along with the port-based analysis above, indicate that the designer of a DD mechanism is free to traverse energetic domains in order to suit the design requirements. Further constraints, such as volume, weight, power supply, and complexity, may impose limitations on the final design.

C. Power Transmission and Efficiency

By definition, the DD topology renders effort through the dissipation of actuator power. Input flow must be imparted by the actuator on the differential in order to render effort. This means that a significant portion of the input energy is simply discarded, and so it is desired that the DD actuator system be designed such that this energy loss is minimized.

For maximum power transmission from the actuator to the differential output, the damper should be fully locked. Accurate force control in this case is only possible if the force at the output of the actuator-drivetrain can be controlled. If such control is possible, then a DD mechanism would not be required to render force (though it could still be used to couple/decouple the actuator from the output). However, one of the initial assumptions was that the required actuator-drivetrain appears as a velocity source and is fundamentally incapable of rendering force control.

The minimum power transmission from the actuator to the output occurs when the damper is disengaged. Thus the output is fully decoupled from the actuator; the actuator can perform no work on the output and is zero percent efficient.

The damper itself only needs to be controllable within the range of efforts required at the output. This implies that the damper need-not be specified to render the full effort range of the actuator – that it may be undersized to suit a specific application. Thus the maximum output effort of the differential is limited by the maximum output effort of the

[2] Low power requirements for operation of the damper itself. It is recognized that power from the actuator will be dissipated through the damper in order to render force.

damper. However, an actuator-transmission combination that is capable of delivering forces far in excess of the output requirements is likely over-sized and would be energetically inefficient in operation. The optimal combination is to match the maximum force output of the motor with the maximum force output of the damper, as seen at the 0-junction.

It also is possible, whether through the geometric parameters of the differential mechanism or through the addition of a dedicated transmission, to "gear-down" the damper relative to the actuator such that a smaller device can control a larger load. The downside to this approach is that this transmission would increase the friction and the reflected inertia at the damper-port, potentially creating the adverse conditions that the mechanism was originally intended to mitigate. As long as the added friction and inertia are less than the original friction and inertia and the added bulk and complexity of the componentry is acceptable, employing a transmission between the differential and the damper may be feasible.

IV. Experimental Validation

A. The HUCA

The Hybrid Ultrasonic motor-Clutch Actuator (HUCA) (Fig. 2) was designed as a first prototype toward a magnetic-resonance-compatible haptic device [15]. While the original application and specifications for this device are quite different from those required of a powerful actuator for, e.g., an active lower limb prosthesis, it is useful for illustrating some concepts behind DD actuation.

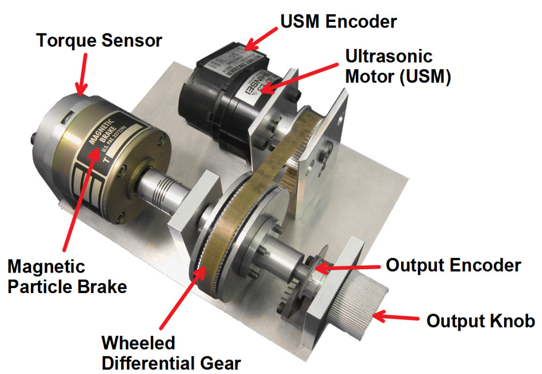


Figure 2. The Hybrid Ultrasonic motor Clutch Actuator (HUCA) [15]

The ultrasonic motor (USM) of the HUCA is non-backdrivable and can be regarded as a velocity source. The USM is coupled through a timing belt to one port of a wheeled differential gear. The second port of the differential gear is attached to a magnetic particle brake, which modulates its braking torque in response to an applied current. The third port of the differential drives the output knob. The gear ratio from the USM to the differential is 2:1.

$$\omega_{USM} = \frac{\omega_{knob} + \omega_{brake}}{2} \tag{2a}$$

$$\tau_{USM} = \tau_{knob} + \tau_{brake} \qquad \tau_{knob} = \tau_{brake} \tag{2b}$$

The maximum torque output for the chosen brake is specified as 34 mNm, while the USM is rated for operation at 50 mNm. Thus, the theoretical maximum torque output at the knob is limited to 34 mNm. The wheeled differential (Table I, row 1) is operated in the region where no wheel slippage occurs and provides zero backlash, low inherent friction and inertia, and a smooth torque-controlled output.

B. Illustrative Experiment

In order to demonstrate a few of the dynamic properties of the DD actuator, the following experiment was performed. A constant initial velocity was generated by the USM. The output knob of the device was blocked such that all of the power output by the USM was dissipated by the magnetic particle brake. The brake was commanded to maintain a constant torque via open-loop control. At 2 seconds, the USM velocity was stepped up to a higher constant value. The measured brake torque and angular speed for eight commanded torques are shown in Fig. 3.

Based on these data, some important observations can be made. The first is that, subject to constraints, the output torque at the knob can be controlled independently of the input velocity. The range of achievable torques is bounded by the minimum and maximum damping provided by the brake and is a function of input velocity. Since the damper is a purely dissipative device, torque at the output can only be generated in opposition to the direction of the input velocity (i.e., velocity must be reversed to change torque direction). Also, the output torque at the knob is not controllable when the input velocity is zero.

Through these observations, it is apparent that there exists some freedom in how the brake input and USM input can be mixed to render torque control. The designer of such a system can then optimize the performance of the system through its control variables based on desired characteristics. This optimization may take place with respect to e.g. energy efficiency, minimum/maximum torque output, or mechanical bandwidth.

A second observation is that while the braking torque remains constant, the angular speed has more than doubled following the speed step. Thus, the power dissipation of the brake has also more than doubled. Excess power dissipation is of utmost concern in applications where energy storage or heat dissipation is an issue.

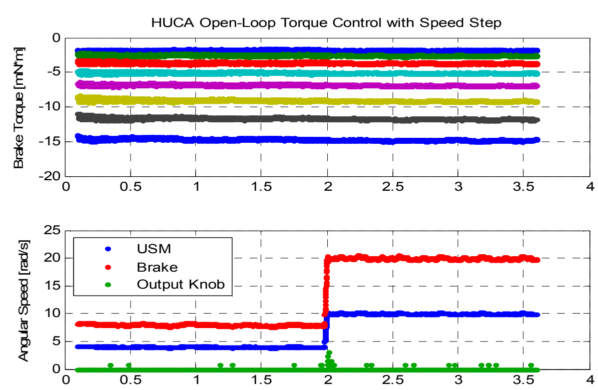


Figure 3. Measured brake torque for 8 different desired constant torques (top) and angular velocity of the USM, brake, and output from one representative trial. The speed step of the USM occurs at 2s. With the DD mechanism, it is possible within bounds to control the brake torque (=output torque) independently of the input speed.

V. Conclusions and Future Work

The use of a DD element can be an effective method for decoupling an actuator with high output impedance from its output. A port-based analysis of a differential coupling between an actuator, a variable damper, and the output reveals one method in which force control can be realized across energetic domains and despite actuator-drivetrain limitations.

Experimentally, it is demonstrated that the torque output on the load can be controlled independently of the input velocity from the actuator. Since the output torque is rendered through the dissipation of input power, application-specific optimization is required to determine how to mix the inputs from the velocity source and damper.

While the components used to construct the HUCA are certainly inappropriate for generating the forces observed in major joints of the human body, the high output impedance of the USM is essentially similar to that of a conventional EM motor with a large reduction, acting as a velocity source. The central concepts of DD actuation can be abstracted from this device and applied to scaled-up systems.

Future work will include the development of an extended analysis of DD and dual-DD [16] actuation, which will enable the tracing of power-flow through the device and optimization of its design and controls. Furthermore, it is desired to evaluate the feasibility of scaling-up and integrating such a device in a compact and lightweight package powerful enough for incorporation with a portable lower limb orthotic or prosthetic device.

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