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Cobotic Architecture for Prosthetics

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Abstract— **We envision cobotic infinitely-variable transmissions (IVTs) as an enabling technology for haptics and prosthetics that will allow for increases in the dynamic range of these devices while simultaneously permitting reductions in actuator size and power requirements. Use of cobotic IVTs eliminates the need to make compromises on output flow and effort, which are inherent to choosing a fixed transmission ratio drivetrain. The result is a mechanism with enhanced dynamic range that extends continuously from a completely clutched state to a highly backdrivable state. This high dynamic range allows cobotic devices to control impedance with a high level of fidelity. In this paper, we discuss these and other motivations for using parallel cobotic transmission architecture in prosthetic devices.**

I. INTRODUCTION

Four key requirements of robotic technologies used for prosthetics, orthotics and rehabilitation robotics are low weight, low energy consumption, safety and controllability. We propose cobotic technology as a transmission architecture that can address all of these issues. Given a set of design criteria for a multi-degree-of-freedom mechanism, such as maximum flow, maximum effort and maximum power, we find that a cobot can meet these requirements with reduced numbers of high power actuators, reduced size requirements for those actuators and increased power efficiency relative to conventional actuation systems [1].

Cobots are robots that utilize the nonholonomic constraints of steered wheels in order to relate the relative velocities of mechanism links. These steered wheels form the basis of a cobotic infinitely variable transmission (IVT). Such a transmission can be smoothly adjusted between an infinite reduction and a zero reduction. Cobotic IVTs have been developed that relate two translational velocities [5], [6], two rotational velocities [3], or a rotational velocity to a translational velocity [1], and have been utilized in many prototype devices. The use and control of nonholonomic constraints (rolling elements) as the basis for passive cobot technology is best summarized by Peshkin et al. [4] and Gillespie et al. [2].

Cobotic technology provides a highly power efficient and weight efficient transmission architecture that can have minimal dissipation and trivial dynamics. Gear trains, timing belt transmissions, hydraulic and pneumatic systems as well as cable systems all have dissipative losses that result in heat and noise generation. In addition, stiction, friction, compliance and backlash in these transmissions add highly nonlinear dynamics to mechanisms. Cobotic transmissions utilizing bearing quality steel components in dry-friction rolling-contact have none of these nonlinearities. Haptic simulations have unusual realism when displayed on the Cobotic Hand Controller, a six-degree-of-freedom haptic display [1]. The crisp distinction between free and forbidden directions of motion is a salient feature of cobots. This performance does not arise from elaborate control algorithms, but from the inherent physical characteristics of the device due to the utilization of nonholonomic rolling constraints in its transmissions.

In the remainder of this paper we discuss the potential weight, energy, dynamic range and safety benefits of cobotic architecture for prosthetics.

II. WEIGHT SAVINGS

Cobotic architecture can lead to significant weight savings, since an infinitely variable transmission paired with a small motor can achieve speeds and loads of a much larger motor with only a fixed reduction. While such a design is still constrained by the maximum mechanical power rating of the motor, this is an acceptable compromise in prosthetics where the extreme operating points of maximum force with minimal velocity and maximum velocity with minimal force, both low mechanical output power conditions, are almost exclusively employed. Using an infinitely variable cobotic transmission can eliminate the need to make compromises on output flow and effort, which are inherent in choosing a fixed transmission ratio. Since an infinite reduction can be obtained, the active lift limitation of the actuator is secondary to the speed rating and power rating.

Additional weight savings can be realized by *parallel* cobotic architecture (Figure 1), which allows a single actuator to deliver power to multiple degrees of freedom. Such a scheme requires $n+1$ actuators for an n-degree-of-freedom system: one large actuator to source power, and n small actuators to modulate the transmissions for each degree of freedom. The joints can still be operated independently, since the transmissions are adjustable smoothly through an infinite reduction, to both positive and negative ratios. The actuators that modulate the transmissions for each degree of freedom can be extremely small and low power, often one to two orders of magnitude smaller than the single power actuator. The transmissions draw power from a single common element actuator as needed, thus reducing the weight and power requirements of the mechanism. Only one set of high power electronics and drive-train components are needed.

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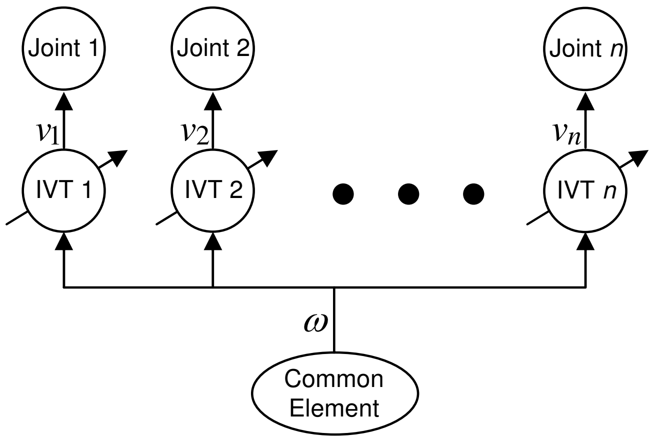

Fig. 1. Parallel power flow from a single large actuator is mediated by a series of infinitely variable transmissions (IVTs), which modulate the power flow to each joint.

III. ENERGY SAVINGS

Parallel cobotic architecture allows for significant electrical energy savings for a variety of reasons, all stemming from the adjustable transmission ratio. If a high output speed but low load is required, the transmission ratio is adjusted to be a small reduction, and the apparent inertia of the motor at the output is small. Thus little electrical power is wasted to spin up and down the inertia of the motor and drivetrain. Conversely, if a low output speed but high load is required, the transmission ratio is adjusted to be a large reduction, and very little motor torque need be applied, thus minimizing resistive heating losses of the motor windings. In fact, infinitely variable transmissions can be adjusted to an infinite reduction, such that no motor torque is required to hold large loads. The transmission itself can act as a clutch, holding loads passively without the need for an additional clutch.

The redundancy of the $n + 1$ actuator parallel cobotic system is utilized to drive the system with the most power efficient set of reduction ratios and common actuator speeds at all times. The common element actuator is operated at an efficient speed nearly all of the time. In addition, the cobotic architecture allows for the ability to both clutch or decouple joints without any additional actuators beyond the low-power steering actuator for each IVT. With cobotic architecture, no electrical power is expended to resist forces in constrained directions. Electrical power is spent only to provide effort along the current motion direction. Rolling constraints in the transmission elements, not electrical power, resist forces orthogonal to the current motion direction. Only joints involved in the current motion direction draw off power from the single common element actuator. Electrical power is consumed only to do work on the inertia of limbs or the outside world, not merely to sustain forces. An extensive comparison of the power and energy efficiency of cobotic versus conventional fixed ratio drivetrains is presented in [1].

IV. SAFETY

Cobotic transmissions have a built in safety feature as well. Since they rely on frictional contacts to transmit power, the preload force at these contacts can be set to slip when a certain output force or joint acceleration is exceeded. This is beneficial to both the safety of the user, and for the drivetrain. Impacts delivered to the limb merely result in slip in the transmissions, since they are backdrivable up to the infinitely variable component that utilizes friction contacts. The variable reduction ratio also allows lower actuator speeds, and therefore lower kinetic energies accumulate in the actuators, reducing the risk of damage to drivetrains during impacts. Finally, the variable ratio drivetrain also allows for the use of smaller actuators that are lighter and less powerful, and therefore are less capable of injuring a user.

V. CONTROLLABILITY

The prosthetics community has seen the use of synergistic prehension and dual ratio drivetrains as alternatives to infinitely variable transmissions for extending the force-velocity regime in which a joint can be operated. Controller implementation for either alternative is not trivial since synergistic prehension requires two actuators and the dual-stage drivetrain requires a discrete switch between ratios. Typical prosthetics also require clutches to hold high loads since the passive lift rating of prosthetic limbs is typically much higher than their active lift. However, these clutches hamper precise control of impedance when engaging and disengaging. Cobot transmissions exhibit this clutching ability without the need for an additional clutch mechanism since they can act as a clutch or brake when set to an infinite reduction. Conversely, if the cobotic transmission is set to a zero reduction, the output is effectively decoupled from the input, therefore putting the mechanism in a passive, backdrivable mode.

The dynamic range of a cobot, with an adjustable reduction ratio, more closely matches the range of natural impedances deliverable by human limbs than a fixed reduction system. Although cobots are controlled as admittance devices, by allowing motions based on the applied force, they do not suffer from the high inertia, friction and backlash that normally exist in a highly geared admittance device. Cobots excel at rendering the wide range of impedances that natural human limbs are capable of. Also, the variable transmission ratio allows for a low apparent inertia (small reduction ratio), a requirement for simulating low impedances, but when strength is required, large reduction ratios can be chosen.

Cobotic devices control the relative velocities of their joints by modulating IVTs with small *steering* actuators, thus directing the single instantaneous motion freedom characteristic of cobots, regardless of the dimension of their configuration space. The parallel cobotic system with $n + 1$ actuators has n adjustable velocity constraints in the transmissions, yielding a single degree of freedom system. The dynamics along this single motion freedom are controlled via a single power injector, or by a human operator in the case of a passive cobot. Rolling constraints in the transmission elements, not electrical power, resist forces orthogonal to the current motion freedom. This leads to a natural stability when rendering virtual constraints, since the instabilities that plague conventional haptic displays, which arise from sampling in discrete time and space and exciting structural resonances, cannot impact any control loops in the constraint directions.

VI. CONCLUSION

We propose cobotic technology as an infinitely variable transmission architecture that when applied to prosthetics will yield reductions in weight, energy consumption, as well as improve safety and controllability. Cobots allow for variable back-drivability, high power efficiency, precise control of output force and velocity at low output speeds, and a single power actuator for multiple degrees of freedom without the need for brakes or clutches. We have previously demonstrated the scalability of cobotic technologies to produce high degree-of-freedom, high bandwidth haptic devices [1], and intend to employ technology gained from these devices in the field of prosthetics.

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