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Advancements in Actuation Solutions for Human-Centric Robotics*

Pablo Lopez Garcia, Amin Khorasani, Stein Crispel, Raphaël Furnémont, Muhammad Usman, Anand Varadharajan, Dirk Lefeber, Bram Vanderborght, and Tom Verstraten

For over three decades, the Brubotics team at Vrije Universiteit Brussel has been at the forefront of human-centric robotics research. Our extensive portfolio encompasses a wide range of innovative approaches designed to enhance the performance, safety, and efficiency of robots across various applications. Through our expertise in developing cutting-edge robotic devices such as exoskeletons, prostheses, and collaborative robots, we have identified a critical issue: conventional engineering design methods often produce systems that are excessively heavy and bulky, resulting in limited productivity, high costs, and significant energy demands. These issues are predominantly linked to the actuation systems. Consequently, our team has concentrated on pioneering advancements in actuation technology to reduce mass and size, lower energy consumption, and improve safety, productivity, and cost-effectiveness. In this extended abstract, we provide a concise overview of our lab's key achievements in this area, both past and present.

Historically, **compliant actuation** has been an important research avenue for Brubotics. A first step consisted in the development of the Pleated Pneumatic Artificial Muscle (PPAM), a membrane that expands radially and contracts axially when inflated. This type of actuator achieves high force density, controllable stiffness, and was most notably used for the bipedal robot Lucy [1]. Since the 2010s, Brubotics has directed its efforts towards electrical elastic actuators that have high power density, are easy to control, and are tailored towards human-centered robotics. We developed the patented Mechanically Adjustable Compliant and Controllable Equilibrium Position Actuation (MACCEPA) [2], an actuator that has a simple construction but allows to control the equilibrium position of the actuator and its stiffness separately. Over the years, Brubotics has finetuned this concept for high torque density and energy efficiency. The MACCEPA has been implemented in active lower-limb prostheses [3], exoskeletons [4] and bipedal robots [2]. The integration of **locking mechanisms** to these systems can result in a substantial upgrade of their performance [5].

Another relevant research avenue for the Brubotics team has been the development of **redundant actuators**. Unlike traditional servo-drive actuators, redundant actuators utilize two or more motors to drive the output. This additional design degree of freedom can be exploited to increase the energy efficiency and safety of the actuator. Redundancy can be introduced in two ways. Kinematic redundancy implies that the output speed is a weighted sum of the speeds of the input motors. Static redundancy implies that the torque of the input motors is added up to generate the output torque.

A specific type of kinematically redundant actuator studied in our lab, which we dubbed the "**dual-motor actuator**" (DMA), consists of two DC motors connected via a differential mechanism. This setup results in a kinematically redundant actuator [6]. By integrating brakes after each motor, DMAs as the one shown in Fig.2 can operate in distinct regions: high torque at low speeds and high speeds at moderate torque. This adaptability is particularly beneficial for applications such as collaborative robots (cobots) and exoskeletons. By distributing power between motors optimized for specific speed-torque regions, DMAs achieve high energy efficiency. The brake system allows one motor to be idle without power consumption, and disengaging the brakes activates full dual-motor operation, enhancing maneuverability albeit at the cost of increased energy use. Selecting lightweight yet powerful motors and gearboxes is essential for balancing mass reduction and energy efficiency [7]. This is crucial for wearable robots where weight impacts usability. Optimizing gear ratios and employing high-efficiency motors minimizes energy consumption, making the system more sustainable. DMAs can optimize speed distribution, thus reducing reflected inertia compared to single-drive actuators. Lower reflected inertia allows the actuator to respond swiftly to control inputs and external forces, reducing impact forces during collisions and enhancing human-robot interaction safety [8].

The **Series-Parallel Elastic Actuator** (SPEA) is another successful actuator concept from our lab. Its statically redundant variant, the +SPEA, places multiple series elastic actuator units with locking mechanisms in parallel [9]. Parallel springs provide part of the output force without electrical energy. Each locked unit acts as a parallel spring with a

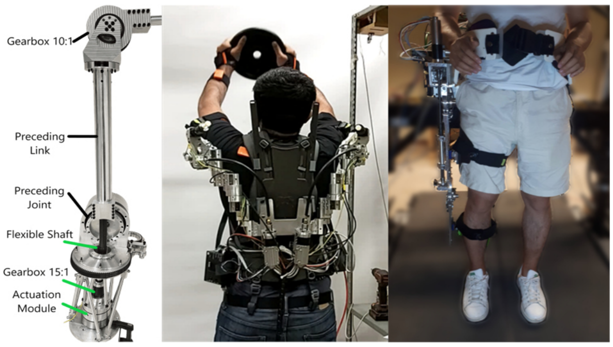

Figure 1: Remote Actuation at Brubotics

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All Authors are with the Robotics and Multibody Mechanics team of the Vrije Universiteit Brussel, Ixelles, 1050, Belgium, and members of IEEE.
V.B. is with IMEC, Leuven, 3001, Belgium
All other Authors are with Flanders Make, Heverlee, 3001, Belgium

Corresponding author:
P.L.G., email: pablo.lopez.garcia@vub.be, phone: +32 499 741816.

configurable resting length, allowing the average force to be actively varied. This reduces total energy consumption for tasks with high forces and low accelerations but adds complexity due to the large number of motors. The iSPEA variant uses an intermittent mechanism to reduce the number of motors to one [10], whereas the SPECTA variant explores the additional potential of using a constant torque spring [11]. Although this decreases versatility, it maintains high energy efficiency for tasks like pick and place.

In recent years, Brubotics has also explored various hardware solutions based on the combined use of elastic elements and **remote actuation** to reduce moving mass and energy consumption. Typical solutions combine spring elements with cable/belt pulley transmissions, resulting in a relatively high mechanical complexity [12]. Flexible shafts are slender and torsionally compliant, offering a simpler, single-element solution. Our team has developed several devices that incorporate these **flexible shafts** as transmission components (Fig. 1). In the context of the ELYSA project, a robot arm with a 1:1 payload-to-weight ratio was developed, capable of lifting 18 kg using a torque-dense joint remotely actuated with a flexible shaft [13, 14]. We also designed an occupational upper body exoskeleton and a lower limb rehabilitation exoskeleton incorporating flexible shaft-based remote actuation [15]. These solutions relocate the mass of the motors, drive electronics and batteries to the waist to decrease metabolic energy consumption. Furthermore, the flexible shaft introduces intrinsic joint compliance, a desirable property in wearable robots.

To fully leverage lightweight electric motors, Brubotics also explored **high-ratio transmissions** to convert the high speeds of small and light motors into high torques. In most high-torque, moderate-speed applications, current high gear ratio transmissions suffer from low efficiency, non-backdrivability, and excessive weight [16]. To address these issues, we have developed the patented *R2poweR* Compound Planetary Gear Train (C-PGT) gearbox technology [17] that is currently involved in its valorization process through our spin-off AILOS and can be seen in Fig. 2. This innovative gearbox enhances actuator energy efficiency by reducing internal power flows and optimizing gear meshing stages [18]. The *R2poweR* technology achieves a gear ratio exceeding 200:1 without compromising efficiency (>80%) or weight (<700g). Additionally, the usability of this gearbox as a power-split device for redundant actuation principles has also been explored to further reduce energy consumption. The integration of a redundant actuation mechanism through a high-ratio gearbox introduces extra design flexibility to optimize performance criteria. Redundant kinematic DOF can be introduced to reduce the reflected inertia of the drivetrain, in addition to static DOFs, which can be exploited to is used to minimize actuator weight. As such, the operating range of the motor can be reshaped to match the task requirements [5].

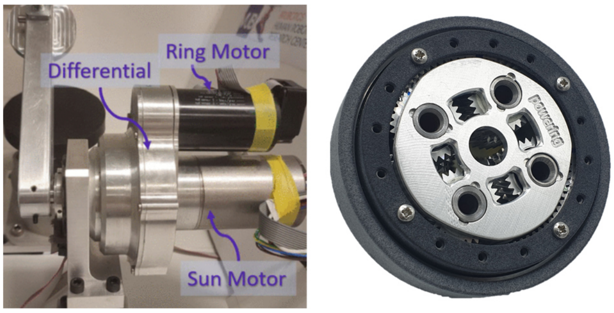

Figure 2: Brubotics' dual motor actuation (left) and high-ratio, backdrivable *R2poweR* gearbox (right).

In conclusion, throughout the past 30 years, Brubotics has emerged as one of the leading research teams in the domain of actuation for human-centered robotics. Our research group will continue these endeavors, with a particular focus on addressing the challenges of wearable robotics and collaborative robots. Building on our extensive expertise in robotic needs and actuator components and concepts, we aim to surpass the performance of current devices by implementing more holistic design processes. Additionally, we will persist in seeking breakthroughs in component designs to push the boundaries of what is achievable with today's technology.

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