Replacing BLDC Motors with Mechanical Transmission Systems in Robotic Hands

Léo Mayques

May 2026

Abstract

Recent advances in Large Language Models have considerably increased interest in general-purpose robotics. While remarkable progress has been made in robot control, one important obstacle remains: robotic hands capable of combining human-like strength, precision and dexterity remain difficult to design and manufacture. Existing solutions generally rely on one actuator per degree of freedom, which leads to increasingly difficult compromises between compactness, strength and the number of degrees of freedom as robotic hands become more sophisticated.

In the present paper, we investigate an alternative actuation paradigm based on separating power generation from motion control. Instead of assigning one power actuator to each degree of freedom, mechanical power is distributed from a single central motor while smaller auxiliary actuators determine where that power is transmitted. We show that such an architecture is only advantageous under a specific set of mechanical conditions, leading to a class of transmission systems which we call **Positive Mechanical Transmission (Positive MT)**.

We first identify the mechanical conditions under which Positive MT can constitute a viable alternative to conventional one-actuator-one-motor architectures. We then derive the corresponding design principles and present a practical implementation, called the **Actron**. Finally, we discuss the principal advantages and limitations of the proposed architecture, most notably the fixed relative speed between actuators and the angular-precision limitation introduced by positive mechanical engagement. The proposed approach suggests that decoupling power generation from motion control may provide a viable alternative for future high-degree-of-freedom robotic systems.

Contents

1 Introduction: Decoupling Power Generation from Motion Control

One of the most remarkable features of the human hand is its unique combination of strength and dexterity. Most adults can easily lift tens of kilograms with a single hand, while the hands of a watchmaker can manufacture and assemble the parts of a mechanical watch. Another remarkable property of the human hand is its versatility. It can be used to grasp heavy objects, turn a screwdriver, press a keyboard or insert a needle into a patient's arm. This remarkable adaptability stems from one physical characteristic: a very high **Density of Degrees of Freedom (DoDoF)**. The human hand possesses no fewer than 23 degrees of freedom, all packed within the relatively small volume of the hand and forearm.

The central challenge in robotic hand design is therefore to achieve a sufficiently high DoDoF while maintaining human-like strength, precision and compactness. The dominant solution in current robotics is to assign one actuator—typically a Brushless DC (BLDC) motor—to each Degree of Freedom (DoF). Throughout this paper, we refer to this architecture as the **One Actuator One Motor (1A1M)** approach.

The 1A1M architecture has the advantage of being conceptually simple. Each joint inherits the flexibility of its own actuator, allowing independent control of position, speed and direction. However, this flexibility comes at the cost of increasing mechanical complexity. As the number of actuated joints increases, the available volume inside the hand and forearm must be shared between a growing number of motors. In practice, this leads to an increasingly difficult compromise between strength and DoDoF, which can only be mitigated through careful mechanical design.

The present work explores a different actuation philosophy. Rather than requiring every actuator to both generate mechanical power and control motion, these two functions are separated. Mechanical power is supplied by a single central motor, while smaller auxiliary actuators determine where that power is transmitted. The resulting architecture relies on mechanical transmission systems, but the central idea is the decoupling of power generation from motion control.

This separation is not advantageous for arbitrary transmission systems. Instead, we show that it becomes competitive only under a specific set of mechanical conditions, leading to a particular class of transmission systems which we call **Positive Mechanical Transmission (Positive MT)**. It is within this operating regime that mechanical transmission can compete with, and potentially outperform, the conventional 1A1M architecture.

We first identify the mechanical conditions required for Positive MT to constitute a viable alternative to conventional 1A1M architectures. We then derive the corresponding design principles and present one practical implementation, which we call the **Actron**. Finally, we discuss the principal advantages and limitations of the proposed architecture, as well as its possible applications to robotic hands.

2 Mechanical Principles: Using mechanical transmission to distribute force

Before introducing the proposed architecture, it is useful to briefly discuss how force is currently transmitted in robotic hands.

In the industry, the 1A1M approach is generally implemented in two different forms, depending on the placement of the actuators relative to the hand. One possibility is to place all motors directly inside the hand itself. This requires every actuator to fit within the limited volume available in the fingers, palm and wrist. The alternative is to place the motors in the forearm and transmit the mechanical power to the joints through tendons. This architecture more closely resembles the anatomy of the human hand and allows the use of larger, more generic actuators. Tendon-driven systems are therefore generally capable of delivering greater force while remaining relatively compact.

Since Positive MT naturally relies on generic actuators rather than highly integrated motors, it also naturally lends itself to tendon-driven architectures.

2.1 The actuation principle

The transmission of mechanical power from one location to another is an old and well-established engineering concept [1]. Mechanical transmission systems exist in many different forms, including belts, ropes, chains, shafts and gear trains. Others rely on direct contact between solid parts, as is the case for gears or clutch mechanisms.

Likewise, the use of a common mechanical power source to actuate several independent mechanisms is not a new idea. It was already employed in historical automatons [2] and in early industrial factories, where a single power source was used to drive several independent machines [7].

The key idea explored in the present paper is therefore not the use of mechanical transmission itself, but rather a different way of distributing mechanical power inside a robotic hand. Instead of assigning one power actuator to each degree of freedom, a single central motor provides the mechanical power for the entire system. The role of the remaining actuators is no longer to generate force, but simply to determine where that force is transmitted. In that sense, the proposed architecture decouples power generation from actuation.

Each degree of freedom therefore still requires a small electrical actuator. However, these auxiliary actuators no longer drive the joints directly. Their sole function is to engage or disengage the corresponding transmission, much like the driver's hand engages first gear in a manual transmission. As will be shown in the following sections, this change in architecture makes it possible to replace many power actuators by a single central motor, while preserving independent control of the different joints.

2.2 Positive MT

As discussed above, mechanical transmission systems exist in many different forms. However, most solid-part transmission systems can be divided into two broad families. The first, called *positive drive*, relies on the mechanical engagement of mating features, as in gears. The second, called *friction drive*, transmits power through friction between two mating surfaces, as in the disc clutch of most manual cars[1].

The distinction is of particular importance here because the viability of the proposed architecture depends directly on the force required to engage the transmission. In positive drives, the actuating motor only needs to overcome the friction generated during engagement and disengagement. In friction drives, however, the engagement force must itself generate sufficient friction to prevent slippage under load.

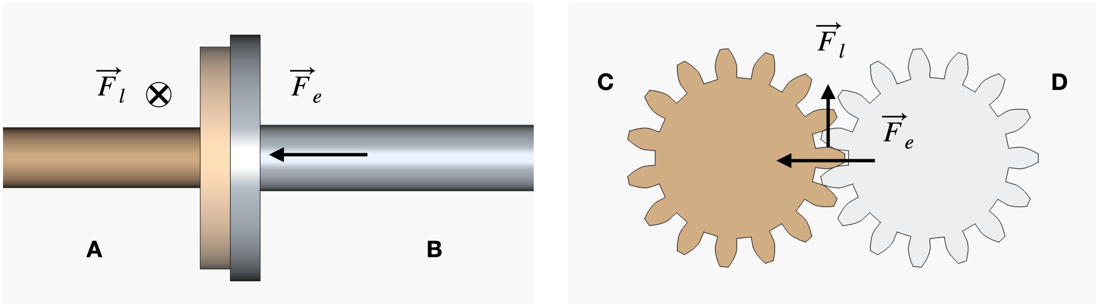

Figure 1: A generic example of the friction drive (on the left) and of the positive drive (on the right)

Fig. 1 illustrates the difference between friction and positive drives. Parts B and D correspond to the elements connected to the moving subsystem (e.g. a finger joint), while parts A and C are connected to the central power source. In both cases, $\vec{F_e}$ denotes the engagement force applied by the auxiliary actuator.

In the friction-drive case, the engagement force must generate a friction force sufficiently large to overcome the loading force $\vec{F_l}$, leading to

$$F_e \geq \frac{F_l}{\mu}. \tag{1}$$

In the positive-drive case, by contrast, the engagement force only needs to overcome the tangential friction generated by the loading force,

$$F_e \geq \mu F_l. \tag{2}$$

For typical values of the friction coefficient μ, friction drives therefore require engagement forces several times larger than the transmitted load. Although this difficulty can be mitigated through mechanical advantage, doing so does not reduce the power required from the actuating motor for a given engagement time. Positive drives, by contrast, can require engagement forces an order of magnitude smaller than the transmitted load when appropriate materials are used.

This property makes it possible for relatively small actuators to control the output of a much more powerful central motor. It is precisely this operating regime that motivates the present work. We refer to transmission systems satisfying these conditions as operating in the **Positive Mechanical Transmission (Positive MT)** regime.

This advantage is accompanied by an important mechanical limitation. Unlike friction drives, positive drives cannot engage continuously, but only when the mating features are properly aligned. Mechanical engagement therefore introduces an intrinsic delay, which must be taken into account during the design of the transmission. We return to this limitation when discussing practical implementations of the Positive MT architecture.

2.2.1 Continuous-Speed MT Drives

The transmission systems discussed above are binary: they only allow the corresponding mechanism (e.g. a finger joint) to be either engaged or disengaged.

One of the principal advantages of the 1A1M architecture is that each actuator independently controls not only the position of the joint, but also its speed and direction of motion.

The most natural way of recovering a similar level of controllability within an MT architecture is to employ continuously variable mechanical transmissions. Such transmissions are used in a number of engineering applications, including some cars and bicycles. CITATION. However, existing continuous-speed transmission systems are generally too large, heavy and mechanically complex to be practical in robotic hands with a high density of degrees of freedom. For this reason, they are not considered further in the present work.

2.3 Positive MT: A Practical Implementation

Having identified the mechanical conditions under which Positive MT becomes advantageous, we now consider one possible implementation. The goal is to distribute mechanical power from a single central motor to the different joints of a robotic hand while preserving independent control of each degree of freedom.

Several mechanisms may be considered to distribute power from a central source, including shafts, chains, gear trains and slider-crank mechanisms. In the present application, however, a large number of mechanical subsystems must be connected along a common transmission line. Chains are generally not intended for such architectures, and complex chain paths are difficult to implement efficiently [1]. Long gear trains suffer from cumulative losses and mechanical complexity, while slider-crank mechanisms require relatively bulky moving components [1]. Shafts therefore emerge as a particularly attractive solution, providing a robust and compact means of distributing mechanical power.

Assuming that power is distributed by a rotating shaft, the remaining design problem is to determine how each mechanical subsystem can be independently engaged and disengaged. The conditions established in the previous sections strongly constrain the possible solutions. The transmission must operate in the Positive MT regime, friction drives are therefore excluded, and the mechanism should ideally allow bidirectional actuation while remaining compact enough for a high-DoDoF robotic hand. One architecture satisfying these requirements is shown in Fig. 2. We refer to this mechanism as the **Actron**.

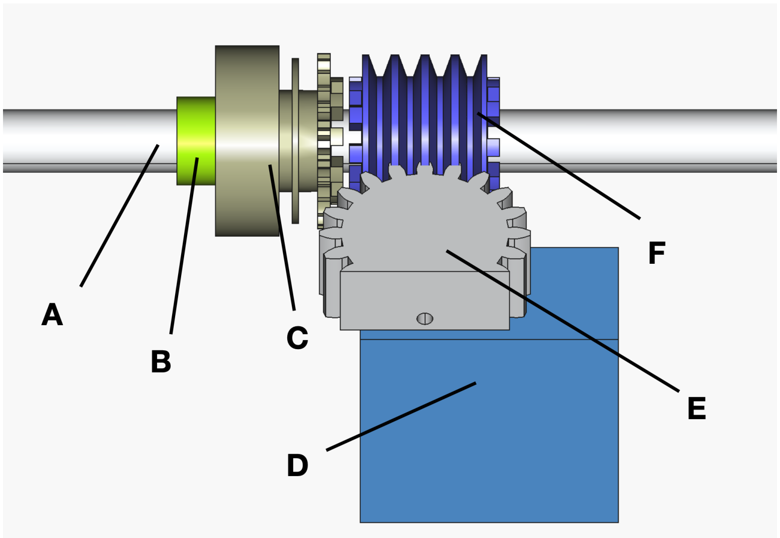

Figure 2: **Basic design of the Actron.** Part A is the rotating shaft supplying mechanical power. Part B is a ball bearing allowing Part C to rotate freely about the shaft. Part C is connected to the tendon driving the mechanical joint. Part D is a generic servo motor controlling the position of the sliding element F through screw E. Part F is coupled to the shaft by a parallel key, allowing axial motion while remaining rotationally locked to the shaft. When the servo rotates E, F is displaced towards C, mechanically engaging the tendon with the rotating shaft. A locking mechanism may also be added to prevent rotation while disengaged, although it is omitted here for clarity.

The mechanism shown in Fig. 2 naturally extends to bidirectional actuation by adding a second output element C' on the opposite side of the shaft. Connecting the tendons of C and C' to opposite sides of the same joint makes it possible to actuate the joint in both directions. Compared with the naive solution of duplicating the entire mechanism for each direction of motion, this arrangement is substantially more compact. It is also mechanically safer, since the same joint cannot accidentally be actuated simultaneously in opposite directions.

One apparent limitation of the proposed mechanism is that Part C is free to rotate while disengaged. Consequently, the corresponding joint cannot maintain a fixed position under external loading. This difficulty can be addressed by introducing a simple locking mechanism preventing Part C from rotating whenever it is disengaged from the shaft. Such a mechanism requires little additional space and ensures that the position of the joint is determined exclusively by the transmission itself rather than by external forces.

Angular Precision and Engagement Delay

As discussed previously, one of the principal limitations of Positive MT is that engagement can only occur when the mating features are properly aligned. Unlike friction drives, positive drives therefore introduce an intrinsic mechanical delay. The practical consequences of this limitation become clearer once a concrete implementation is considered.

Since the tendon is directly wound onto Part C, the rotational speed of the shaft cannot be arbitrarily increased without causing excessive joint velocities. Furthermore, each engagement must remain sufficiently short to avoid overextending the tendon. The minimum shaft diameter is itself constrained by mechanical strength. Together, these considerations imply that a typical joint motion will occur over approximately one shaft revolution. Unfortunately, the engagement delay introduced by the discrete mating geometry is of the same order of magnitude.

The most direct way of reducing this delay is to increase the number of mating features. Doing so, however, necessarily reduces the size and mechanical strength of each feature, leading to a trade-off between angular precision and load capacity. Consequently, angular precision becomes an important design parameter of any Positive MT implementation.

Tuning Individual Joint Speeds

Although the relative speeds of the different mechanisms are fixed, the tendon velocities required by the different joints of a robotic hand are generally not identical. The wrist, for example, must typically undergo much larger displacements than an individual finger joint. Within the proposed architecture, these differences can be accommodated simply by adjusting the diameter of the tendon groove in Part C. Larger groove diameters produce proportionally larger tendon displacements for each shaft revolution. While straightforward in principle, determining the optimal groove diameters requires careful mechanical tuning and experimental validation.

3 Discussion

The analysis presented above suggests that robotic hand actuation can be approached through two fundamentally different architectures. In the conventional **One Actuator One Motor (1A1M)** approach, every actuator is responsible both for generating mechanical power and for controlling the corresponding joint. In the proposed **Positive Mechanical Transmission (Positive MT)** architecture, these two functions are separated. A single central motor provides the mechanical power, while the remaining actuators merely determine where that power is transmitted.

This decoupling of power generation from actuation is the central idea behind the proposed architecture. It gives rise to a different set of mechanical constraints and design trade-offs than those encountered in conventional 1A1M systems. Table 1 summarizes the principal characteristics of the different approaches.

Advantages

The principal advantage of Positive MT is that it decouples power generation from mechanical control. Since the small actuators no longer provide the transmitted force themselves, they can be substantially smaller than the central motor. This power multiplication is what makes Positive MT competitive with conventional 1A1M architectures, despite the additional transmission mechanism.

Table 1: Comparative table

	1A1M	Positive Drive	Friction Drive	Continuous Speed Positive Drive
Compactness	Medium-high	Medium-high	Low	Low
Fixed relative speed	No	Yes	Yes	Yes
Bidirectional control	Yes	-	-	No
Angular precision limit	No	Yes	No	No
Power multiplication	No	Yes	No	No
Back-drivability	Possible	Not possible	Not possible	Not possible

This reduction in actuator size has a number of practical consequences. First, it relaxes the dimensional constraints imposed by high-DoDoF robotic hands, allowing a more compact overall architecture. Second, it makes it possible to rely on relatively small, generic actuators rather than highly specialized motors. This has the potential to reduce manufacturing costs while simplifying prototyping and deployment through the use of readily available off-the-shelf components.

Limitations

The proposed architecture also introduces a number of important design constraints. Some are fundamental consequences of the Positive MT concept itself, while others arise from the particular implementation considered in this work.

The principal open question concerns the fixed relative speed between the different actuators. Although the overall speed of the robotic hand remains fully controllable through the central motor, the relative speeds of the different joints are determined by the transmission geometry. At first sight, this appears to be a significant limitation. However, it remains unclear whether independent relative actuator speeds are actually required for most human manipulation tasks. To the best of our knowledge, this question has not yet been explicitly addressed in the robotics literature. Should future work show that fixed relative speeds are sufficient for a large class of manipulation tasks, this apparent limitation would become considerably less restrictive.

The second important limitation is the angular-precision constraint introduced by positive mechanical engagement. As discussed previously, reducing the corresponding delay requires increasing the number of mating features, which in turn decreases their mechanical strength. The resulting compromise between engagement precision and load capacity therefore becomes an important design consideration in any Positive MT implementation. Unlike the fixed-speed constraint, however, this limitation appears primarily as an engineering trade-off rather than a fundamental obstacle.

Finally, some practical limitations of the proposed architecture can be alleviated through improved mechanical design. The bidirectional Actron presented in this paper illustrates this point. Although a naive implementation would require two complete mechanisms per degree of freedom, the proposed design achieves bidirectional actuation with only a modest increase in mechanical complexity.

4 Conclusion

The present paper has explored the possibility of replacing the conventional One Actuator One Motor (1A1M) architecture by a different actuation paradigm based on Mechanical Transmission (MT). Rather than assigning one power actuator to each degree of freedom, the proposed architecture distributes mechanical power from a single central motor while using smaller auxiliary actuators to control the transmission of that power.

We have shown that not every MT architecture is capable of competing with the conventional approach. Instead, the analysis naturally leads to a particular class of transmission systems, referred to as **Positive Mechanical Transmission (Positive MT)**, for which relatively small actuators can control forces substantially larger than their own output. It is this operating regime that makes MT a plausible alternative to 1A1M architectures in robotic hands with a high density of degrees of freedom.

The proposed architecture introduces its own set of design constraints, most notably a fixed relative speed between actuators and an angular-precision limitation associated with positive mechanical engagement. These limitations represent the principal trade-offs associated with separating power generation from motion control. At the same time, Positive MT offers the possibility of reducing actuator size, simplifying mechanical integration and relying on more readily available off-the-shelf components.

More generally, the present work suggests that robotic actuation need not necessarily be based on the assumption that every actuator must both generate mechanical power and control motion. Decoupling these two functions constitutes an alternative actuation philosophy, whose practical relevance remains to be explored.

5 Outlook

Several important questions remain open. The first, and perhaps most fundamental, concerns the fixed relative speed imposed by the Positive MT architecture. It remains unclear whether independently varying the speed of every joint is truly necessary for most human manipulation tasks, or whether a robotic hand with fixed relative joint speeds could still perform a sufficiently broad range of motions. Answering this question would help determine the range of applications for which Positive MT is an appropriate actuation strategy.

The concepts presented in this paper also require experimental validation. Ultimately, only the construction of a working prototype, or at least of a sufficiently realistic digital twin, can determine whether Positive MT can successfully compete with conventional 1A1M architectures in practice. In particular, the angular-precision limitation, the engagement delay and the tuning of the different transmission ratios must all be evaluated in an actual mechanical implementation.

Finally, although the present work has focused exclusively on robotic hands, the underlying actuation philosophy is considerably more general. Any robotic system combining a high density of degrees of freedom with demanding constraints on size, weight or actuator integration could potentially benefit from separating power generation from motion control. Investigating whether Positive MT can be extended beyond robotic hands therefore appears to be a promising direction for future work.

References

[1] Richard G. Budynas and J. Keith Nisbett. *Shigley's Mechanical Engineering Design*. McGraw-Hill Education, 11 edition, 2019.

[2] Alfred Chapuis and Edmond Droz. *The Jaquet-Droz Mechanical Dolls*. Neuchâtel, 1958.

[3] Peter Corke. *Robotics, Vision and Control: Fundamental Algorithms in MATLAB*. Springer, 2 edition, 2017.

[4] John J. Craig. *Introduction to Robotics: Mechanics and Control*. Pearson, 4 edition, 2018.

[5] Arthur E. Fitzgerald, Charles Kingsley Jr., and Stephen D. Umans. *Electric Machinery*. McGraw-Hill, 7 edition, 2013.

[6] Austin Hughes and Bill Drury. *Electric Motors and Drives: Fundamentals, Types and Applications*. Elsevier, 5 edition, 2019.

[7] Louis C. Hunter and Lynwood Bryant. *A History of Industrial Power in the United States, 1780–1930. Volume 3: The Transmission of Power*. MIT Press, Cambridge, MA, 1991.

[8] Robert C. Juvinall and Kurt M. Marshek. *Fundamentals of Machine Component Design*. Wiley, 7 edition, 2020.

[9] Robert L. Norton. *Machine Design: An Integrated Approach*. Pearson, 6 edition, 2020.

[10] Bruno Siciliano, Lorenzo Sciavicco, Luigi Villani, and Giuseppe Oriolo. *Robotics: Modelling, Planning and Control*. Springer, 2 edition, 2016.

[11] Wei Tong. *Mechanical Design and Manufacturing of Electric Motors*. CRC Press, 2 edition, 2022.