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REVOLUTION IN MOTION

MOTUS LABS M-DRIVE BRINGS VALUE TO THE ROBOTICS INDUSTRY

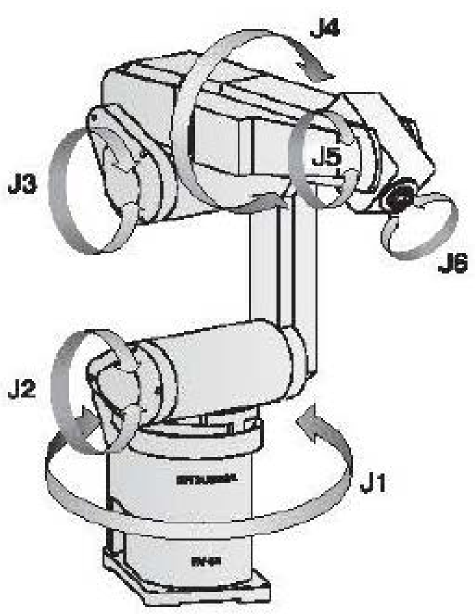
TODAY'S ROBOTS ARE SLOW, AND THEIR WORKSPACES ARE LIMITED

This statement may seem somewhat shocking. But while there have been tremendous advances lately in fields such as machine learning and vision systems, most articulated robots cannot move much faster than the earliest robots introduced in the 1950s. Why is this?

The simple answer is that components are not available to make truly lightweight robot arms. Some progress has been made in lightening the links between joints through the use of composite materials, but the active components in robot joints - actuators - have not fundamentally changed for several decades. There is so little innovation in this area, that robot designers do not even acknowledge that there is a problem. A problem without a solution is no longer seen as a problem, but rather a constraint. Designers simply see no way around it.

The hidden costs of these shortcomings can amount to thousands of dollars. Based on the ROI model used by the Robotic Industries Association, even a moderate increase in speed can result in an added lifetime value equal to or exceeding the cost of the robot.

ROBOTIC ACTUATORS - THE MUSCLE BEHIND ROBOTS



Source: International Federation of Robotics, 2019

The actuators used today in articulate robot arms, that is arms with six or seven joints, usually are a combination of a motor and a drive/transmission. Actuators are generally described in terms of the amount of torque they are able to produce. Torque is measured in Newton meters (Nm) and can be understood as a "turning effect" that produces a rotational force. Each actuator is responsible for moving the portion of the robot arm ahead of it. It is easy to see that the further away an actuator is from the end of the robot arm, the more weight it must move.

The conundrum in robot arm design is that the more weight an actuator must move, the heavier it becomes itself. Since each actuator down the arm is moving more weight, each successive actuator becomes heavier and heavier, imposing its own weight burden on the next actuator above it. A small to mid-size robot might require actuators able to supply between 20 and about 400 Nm of torque. Larger robots might require actuators able to provide thousands of Newton meters.

TORQUE DENSITY IS THE KEY TO ROBOT PERFORMANCE

An important measure of actuator performance is something called torque density. The torque density of an actuator is equal to the amount of torque it is able to deliver divided by its mass. If, for example, an actuator is able to produce 50 Nm of torque and weighs 5 kg we would say that it has a torque density of 10 Nm per kg.

An actuator usually includes a motor along with a transmission. The motors used in robot arms are able to produce small torques at very high speeds. The purpose of the transmission is to convert the low torque, high speed energy of the motor to a much higher torque at lower speed. The gear ratio of the transmission can be thought of as a torque multiplier. For example, a transmission with a 100:1 gear ratio will step up the torque of a 1 Nm motor to 100 Nm. At the same time, the transmission output would spin at 1:100th of the motor's input speed. For this reason, robot transmissions are sometimes also referred to as speed reducers.

"My intent is to revolutionize the robotic actuator industry to enable new applications and break through old technology limitations."

Carlos Hoefken - Inventor & Co-Founder, Motus Labs

STAGNANT DEVELOPMENT & CURRENT LIMITATIONS OF TODAY'S DRIVES

Contemporary robot transmissions operate on basic principles of gearing that date back to 5th century BC. In 1957, The American inventor C. W. Musser patented a novel new type of gearing that featured a flexible steel element. Dr. Musser's invention, alternately called strain wave gearing, increased the area over which the drive input and output elements meshed. At the time, this was a significant innovation, enabling the output load to be distributed over a larger area than before. This provided for higher torque densities than previous gear drives were able to attain.

Harmonic and Nabtesco drives allow for around 15 to 20% engagement between input and output gear surfaces. With the strain wave drive, however, spur type gear drives seem to have reached a sort of plateau in torque density. Any incremental gains made in torque density since the strain wave drive's introduction have usually been at the expense of compromising other parameters, such as stiffness or efficiency.

"Torque to weight ratio is the key. "

Esben Ostergaard - Co-Founder, Universal Robots

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THE MOTUS LABS BREAKTHROUGH

The Motus M-DRIVE technology provides a radical new means of reducing actuator weight through a new type of drive/ transmission. In order to achieve greater improvements in torque density, a revolutionary new design was invented by Carlos Hoefken.

The Motus M-DRIVE enables up to 80% engagement of input and output. Strictly speaking, M-DRIVE is not a gear drive in the conventional sense. Unlike a strain wave drive, the input surfaces of the M-DRIVE are distributed outside rather than inside the output element and they are set in motion by means of a cam follower mechanism. This arrangement allows the input load to be distributed over 4-5 times the area that is achievable in a strain wave drive. This in turn enables a correspondingly higher torque density: up to four times the torque in the same weight. To date, Motus Labs has been awarded 7 U.S. patents for this novel technology.

The mechanical advantages of the Motus design also offer potential improvements in other performance areas – most notably efficiency and torsional stiffness.

EFFICIENCY

Strain Wave drives produce a lot of heat due to their use of flexible metals – with internal temperatures approaching the limits of what the unit's lubricant is able to sustain. As a result, strain wave drive manufacturers specify hard limits of 90 minutes or less to the time during which the unit can operate continuously. The excess heat generated by strain wave drives also poses challenges for motor suppliers: in order to sustain reasonable motor performance, a safety margin of 20% or more must be assigned to the motor's rated torque. As a result, robot joint designers are forced to purchase more motor torque than they really need and suffer the resulting weight penalty. In contrast the M-DRIVE architecture is designed to run cooler. By using the Motus Labs solution, a robot designer can avoid this situation.

STIFFNESS

Stiffness, or torsional stiffness, describes how much a gear drive deforms when bearing a load. A well-known weakness of strain wave drives is their elasticity, which can introduce mechanical resonances and instabilities at low speeds. Since torsional stiffness generally improves with drive size, a common workaround today for robot designers is to use a drive with more torque than they really need – again introducing unwanted weight and cost. The Motus M-DRIVE design provides higher torsional stiffness because of increased mating surface contact area eliminating the elasticity.

FLEXIBILITY IN MATERIALS

Due to the nature of the design, Motus drives are built with standard alloys and require no precision machining. Motus drives have been built using steel, aluminum, and have been 3D-printed in plastic. The flexibility in materials and simplified manufacturing requirements translate directly into cost savings for Motus' customers, as well as the ability to address unique applications. Motus has been called on in the past to deliver aluminum versions of its drives for drone applications, as well as for applications where non-magnetic materials are needed – such as semiconductor handling and MRI machines.

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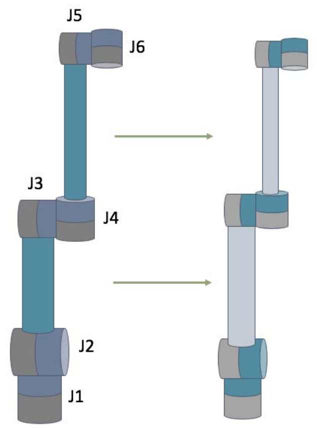
DIRECT ECONOMIC BENEFITS FOR ROBOT MAKERS

When a robot is designed using Motus M-DRIVE, a number of benefits accrue:

- Motors can be "right-sized" without the need for excessive safety margins to accommodate gear drive heat.
- Beginning at the wrist, each actuator needs to provide less output torque – resulting in progressively lower weight gear drives at each joint.
- The need for each actuator to provide progressively less torque lowers the torque requirement for each motor – further driving down cost and weight.



	J1	J2	J3	J4	J5	J6
Torque Needed	Up to 50% less torque required per actuator					
Harmonic	178 Nm	178 Nm	52 Nm	52 Nm	30 Nm	30 Nm
Motus	87 Nm	87 Nm	48 Nm	48 Nm	30 Nm	30 Nm
Actuator Weight	Up to 65% less weight per actuator					
Harmonic	9 kg	9 kg	3 kg	3 kg	2 kg	2 kg
Motus	3 kg	3 kg	2 kg	2 kg	1 kg	1 kg
Actuator Cost	10% to 20% lower cost per actuator					
Harmonic	$670	$670	$511	$511	$440	$440
Motus	$525	$525	$455	$455	$400	$400

As an example, a typical low payload (0-20 kg) robot may see the following benefits when implemented with a Motus solution:

- Up to 50% less torque required per actuator
- Up to 65% less weight per actuator
- 10% to 20% lower cost per actuator

This does not include any additional savings due to "right-sizing" the drives for torsional stiffness – perhaps leading to an additional 10% to 20% cost savings per drive or actuator.

ECONOMIC BENEFITS FOR ROBOT USERS

Motus' advantages allow robot makers to better serve their end customers through:

- Larger robot workspaces through increased reach
- Greater productivity through increased speed
- Longer robot life through decreased wear

Depending on the robot type and installation, the improvements afforded by MOTUS M-DRIVEs can offer savings to the end user equal to or exceeding the cost of the robot. Where do these savings come from?

$40,000 per robot — in system cost savings

$35,000 per robot — in maintenance savings

$75,000 per robot — in additional productivity

Based on Robotic Industries Association ROI model

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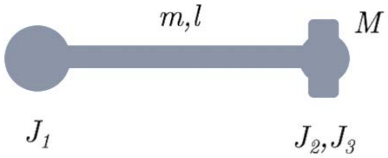
INCREASED REACH

In the figure to the right, M represents the combined mass of two wrist actuators at joints J2 and J3: *l* is the length of the link connected to the wrist actuators; *m* is the mass of the link, which we assume to be uniformly distributed.



Assume, for example, that the link weighs 10 kg, that it is 50 cm long, and that each wrist actuator weighs 3 kg. This would require a torque of about 50 Nm to keep the arm level.

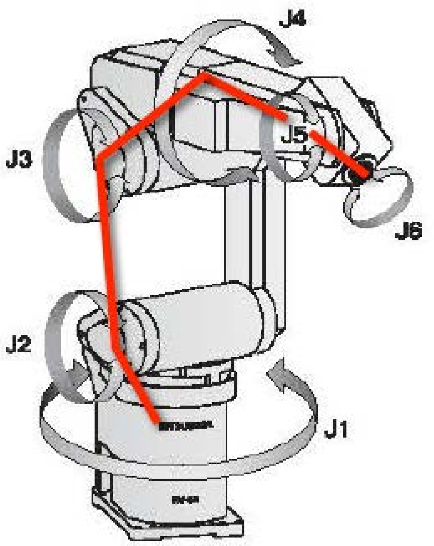
If we consider just the forces required to hold the arm vertical, J1 must supply a torque: $T = \frac{1}{2}mgl + Mgl$

We can see how the wrist actuator masses can impact the allowed link length, l, if we keep J1 torque T fixed: $l = \frac{T}{\left(\frac{1}{2}m + M\right)g}$

The MOTUS M-DRIVE can increase the torque density of the wrist actuators by a factor of two – meaning that their masses decrease by half. This implies that the arm length can increase up to 68 cm – nearly 40% longer. Longer reach means that the robot work cell can be larger, potentially reducing the number of robots required to service a given user facility.

INCREASED SPEED

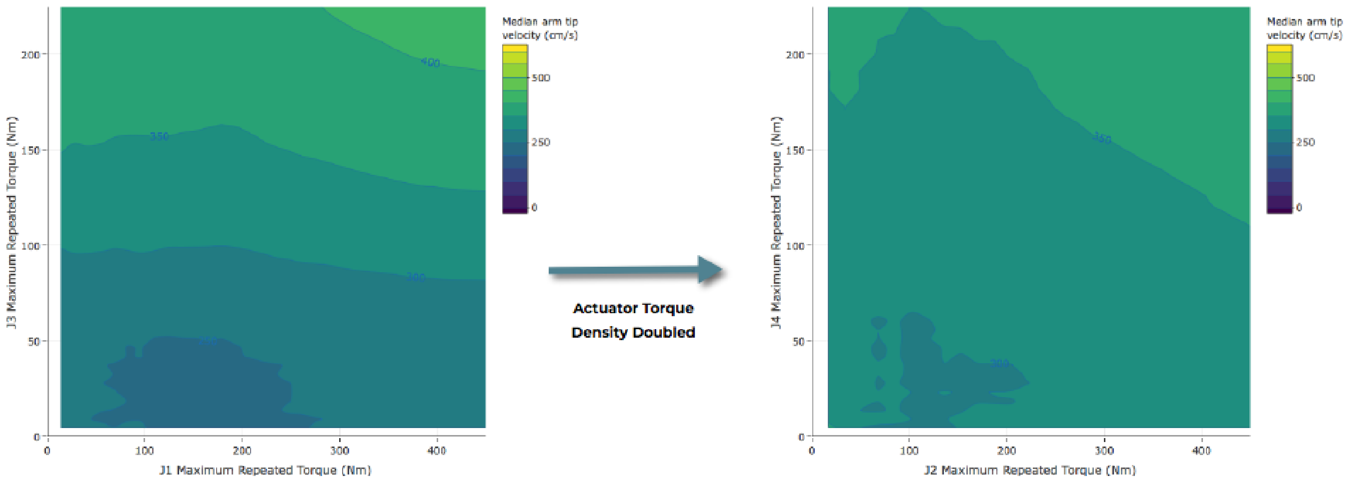
Robot arm speed and acceleration depends directly on the amount of torque each actuator is able to supply to move the weight of each link and joint. Here the conundrum is that the more torque an actuator must supply, the heavier it becomes. As a result, the weight of each successive actuator becomes a drag on the ones that follow it. A reasonable analogy might be trying to run with weight belts on one's knees and ankles.



For example, regarding the robot to the left, there is a cascading effect of actuator weight:

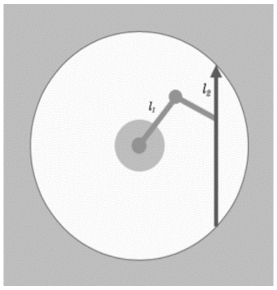
- J5 must move weight of J6
- J4 must move weight of J5 and J6
- J3 must move weight of J4, J5, J6
- J2 must move weight of J3 through J6
- J1 must move weight of J2 through J6

Simulations can reveal how impactful actuator torque density can be. In the simple dual-link simulation below, for example, doubling actuator torque density can increase the median arm speed by 10-30%, depending on the arm configuration.[1]



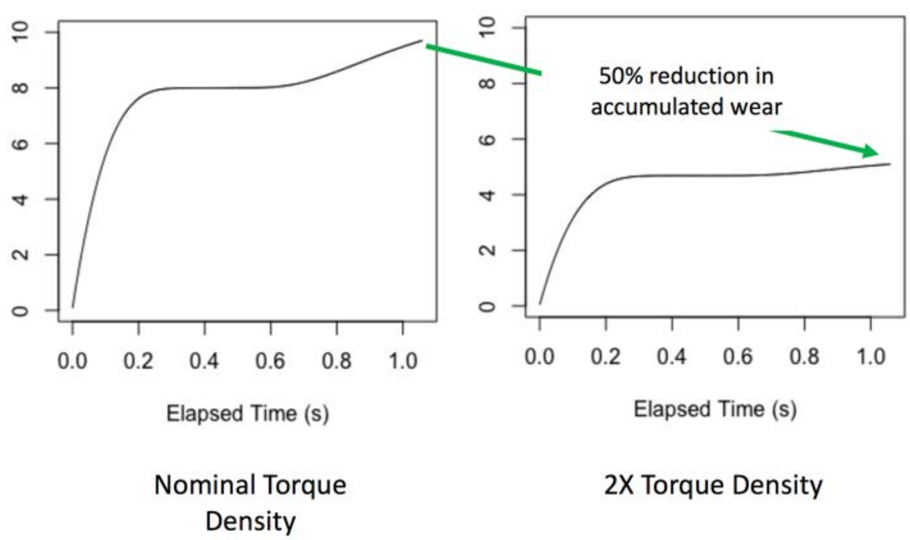
LONGER LIFE

The MOTUS M-DRIVE torque density advantage gives the designer a large safety margin for reliability. Whereas, for example, a conventional Size 17 gear drive might provide around 30 Nm of torque, the Motus drive could provide up to twice the amount of torque in the same size. This additional torque "headroom" translates directly into less drive wear and lower maintenance costs.



The figure to the right represents a robot arm designed to repeat some vertical task, such as painting or welding. The link lengths are 100 cm and 50 cm, and the tip is moving at a speed of 1 m/s. The two figures below [2] depict the amount of wear to the actuator at the elbow joint assuming (a) nominal actuator torque density, and (b) torque density twice nominal.

These results may vary depending on the robot geometry, but in general the robust torque ratings of Motus drives will result in a 20-50% increase in the useable life of the actuator.



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MOTUS M-DRIVE ENABLES INCREASED VALUE TO THE ROBOTICS INDUSTRY

KEY VALUES OF MOTUS M-DRIVE

2X TORQUE DENSITY

80% ENGAGEMENT OF INPUT AND OUTPUT LOAD TO BE DISTRIBUTED 4 - 5 TIMES THE AREA VERSUS A HARMONIC DRIVE

UP TO 50%	LESS TORQUE REQUIRED PER ACTUATOR
UP TO 65%	LESS WEIGHT PER ACTUATOR
10% TO 20%	LOWER COST PER ACTUATOR
10% TO 20%	COST SAVINGS PER DRIVE DUE TO RIGHT-SIZING

- THE MOTUS M-DRIVE ECONOMIC BENEFITS FOR ROBOT USERS CAN WELL EXCEED THE PURCHASE PRICE OF THE ROBOT.
- ROBOTS DESIGNED AROUND MOTUS M-DRIVES ARE ABLE TO ATTAIN LONGER REACH, HIGHER SPEEDS AND LONGER LIFETIMES.
- MOTUS M-DRIVES CAN BE BUILT USING VARIOUS MATERIALS.
- MOTUS M-DRIVES RUN COOLER.
- MOTUS M-DRIVES OFFER IMPROVEMENTS IN EFFICIENCY AND TORSIONAL STIFFNESS.

[1] For a more detailed treatment of this, refer to Motus Labs whitepaper, "Case Studies in Dual-Link Arm Dynamics"

[2] Zancewicz and Hoefken, "Impact of Actuator Torque Density on Expected Robot Life – A Dynamic Model," 2020 5th International Conference on Control and Robotics Engineering, Osaka, Japan