DEVELOPMENT OF CUSTOM-INTEGRATED ROBOTIC ACTUATORS FOR AN ASSISTIVE ROBOT MANIPULATOR

by

Gabriela Davila Albor

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ABSTRACT

DEVELOPMENT OF CUSTOM-DESIGNED INTEGRATED ROBOTIC ACTUATORS FOR 6DOF ASSISTIVE ROBOT MANIPULATOR

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Gabriela Davila Albor

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Under the Supervision of Professor Mohammad Habibur Rahman

The development of wheelchair-mounted assistive robots is currently constrained by significant hardware limitations and the high costs associated with creating custom technologies tailored to specific design needs. Key challenges include the need for lightweight, compact, and aesthetically pleasing designs, reliable control, sufficient payload capacity, and reduced production costs. Designers have only two options for robot joints: buy all components separately, which extends the time needed for design and difficulties modularity, or choose an intergraded actuator joint from the market, where there is not a variety of appropriate options, and those available still have room for improvements in weight, length, and installation. The lightest robot arms lack the use of safety components like brakes and other sensors. Those who use them tend to result in bulky systems. This research aims to address these gaps by developing integrated actuator units for robotic joints tailored to assistive robot arms. The proposed integrated actuators will prioritize compactness, low weight, ease of control, and straightforward installation without compromising mechanical performance. The main criteria for selecting the components used are high quality, slim, lightweight, robust customer support, and compatibility between components. Also, simplifying and minimizing the number of custom parts required in the unit and for installation.

By advancing actuator technology, this work aims to significantly enhance the functionality and accessibility of assistive robot arms, directly improving the quality of life for individuals with disabilities. Moreover, the outcomes of this research have the potential to reduce healthcare costs and inspire advancements in the field of robotics, offering compact, efficient, and cost-effective solutions for the broader landscape of assistive technologies.

Keywords: Robotic Actuator, Integrated Actuator, Assistive Robot, Robot Manipulator, Design, Electric Wheelchair.

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ADA	Americans with Disabilities Act
ADL	Activities of Daily Living
DFM	Design for Manufacturability
DfR	Design for Reliability
DH	Denavit-Hartenberg
DLR	German Aerospace Center
DOFs	Degrees Of Freedom
HCD	Human-Centered Design
HPJ	High-Performance Joint
KAIST	Korean Advanced Institute of Science and Technology
ULLMI	Upper or Lower Limb Mobility Impairments

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Individuals with disabilities that hinder normal mobility account for 1% of the global population [1] and 1.7% of the U.S. population [2], rely on assistive technology, a field dedicated to developing products, devices, and systems that enhance their capabilities and address diverse needs. For example, wheelchairs and prosthetic limbs can improve mobility. The combination of the variety of tools available can be selected for each user's specific requirements [3]. They and their families can benefit from all the tools that bring more independence to their Activities of Daily Living (ADL) [4]. As technology has advanced, many of these solutions have evolved from purely mechanical to mechatronic tools, like wheelchairs to electric wheelchairs, opening the door to even more technological integration to these tools, like the field of robotics, expanding towards the assistive needs, extrapolating the use of industrial robot arms to rehabilitation robots, surgical robots, and social care robots, bringing the need of more technological development of all components to adapt to the particular user case.

Currently, tools like assistive robots can support the caregiver's responsibilities [5], improve their life, and reduce the unpaid caregiving cost of $470 billion per year in the U.S. from informal caregivers like relatives [6]. Also, it is essential to consider that in 2015, in the U.S., each state spent around 34% to 36% of its budget on healthcare [7]. A 5.1% growth in the spending budget is expected from 2021 to 2030, projected to be a national spend of almost $6.8 trillion by 2030 [8].

People with upper or lower limb mobility impairments (ULLMI) tend to use wheelchairs in their ADLs [1]. Therefore, one specific robotics approach, in response to the needs of people with disabilities or advanced age, to help give more autonomy was the development of electric wheelchair-mounted assistive robot arms; this focuses on improving the quality of life for people by implementing designs that facilitate the completion of ADLs, like reaching, grasping, eating, and more [9], which can be challenging without the help of another person (a caregiver). The wheelchair-mounted assistive robot arms industry is led by three major companies: ACCREA Engineering, Assistive Innovations B.V., and Kinova Inc., with a market value of USD 9.8 million in 2022 and a projection of USD 31.4 million by 2032 [10]. Also, Universities have worked on research development in this field, like the University of South Florida with the development of WMRA-I in 2005 [11], with 7-DOF and using DC servomotors with Harmonic drive gearheads as the actuator joint, and later on WMRA-II in 2008, using a carbon fiber links instead of aluminum as in WMRA-I, and using Maxon Precision Motors with Harmonic Drives [12]. As well as the German Aerospace Center (DLR), Institute of Robotics and Mechatronics, with the creation of LWR III, a robot arm used in the EDAN system in 2020, with 8-DOFs and custom embedded actuator joints [13]. The first version of the DLR’s robot arm was the LWR I completed in 1995 [14]. Furthermore, the University of Wisconsin-Milwaukee has developed various 6-DOFs wheelchair-mounted Robot arms using QRob integrated actuators as robot joints [15]. Some other examples of wheelchair-mounted assistive robot arms are Kinova’s Robot Arm “JACO” [16], Assistive Innovations B.V. Robot Arm “iARM” [17], BATEO [18], ARIA v2 [19], and more. Although progress has been made in this field, research is ongoing, and specialized technology is currently available, the market offer still needs to improve to meet the design requirements of assistive robot arms to match the achievements of growth industries.

Assistive robot arms design needs include lightweight, thinner, slimmer, compact design, pleasing aesthetics while providing reliable control, sufficient payload capacity, and lower production cost. Also, although there are models commercially available, there is still the need to enhance manipulability, reduce energy consumption, and ensure foldability when not in use, all while covering the ADLs workspace [15]. Furthermore, this kind of robot arm must adapt to existing architecture, making its physical dimensions a critical factor in how it impacts the surroundings.

Robot arms can be defined by degrees of freedom (DOFs), payload capacity, length or maximum reach capability, workspace, Denavit-Hartenberg (DH) parameters, and other factors. To improve the overall performance of wheelchair-mounted assistive robot arms, it is necessary to get to the root of their composition and hardware and identify the key elements that can most influence them. The technical aspect that covers and impacts all the design requirements of assistive robot arms is the robotic actuator joints used in the design. Their mechanical and physical characteristics are usually a set part of the hardware that will dictate the possible final shapes, sizes, and performance of the assistive robot arm. The development of costume-design actuators that consider installation, electrical connections, environmental conditions, torque requirements, safety, efficiency, and all the wheelchair-mounted assistive robot arm’s design requirements beforehand, is critical to achieve improvements in robot joints can directly impact the technology industry, resulting in the development of new compact wheelchair mounted assistive robot arms that adapt better to the existing environment architecture, occupying less volume without sacrificing payload capacity. The improvements in actuators also benefit the design solutions in other areas as they expand the market solutions that can fit better to the needs, promoting improvements in different systems that were limited by the technology available in the market at the moment of development.

1.2 Existing Solutions and Their Shortcomings

Regarding existing solutions, there is a wide variety of options for commercial and custom-made motors and actuators. Solely looking into actuators, we see that there are electromagnetic geared and directly driven, hydraulic, and pneumatic actuators, among others. Each one with its advantages and limitations, like hydraulic actuator's capacity for high forces while limited by the velocity of action due to the properties of fluids, same with pneumatics, a popular choice in industry settings for their high force, speed, and good power-weight ratio, they still lack efficiency being a system based on the conversion of electrical power to air compression to mechanical movement. In the case of electromagnetic geared drive actuators, the inclusion of gear reduction systems brings other points to the conversation, like backlash, compactness, wear, and regular maintenance for its complexity. On the other hand, direct drive loses most of these issues by not including a gearbox in its assembly, improving efficiency, control, responsiveness, and reliability, but in cases where higher torque is required, it also loses points needing bigger, heavier, and more expensive motors in comparison to other options available.

In a recent paper, Yuan Z analyzed these alternatives in 2023 on the paper “Current status and prospects of actuator in robotics” [20] and compared them based on critical characteristics that can be defined early on during the early design stage of any robotic or mechatronic system, see **Table 1**. As said before, each one has advantages and shortcomings to be taken into account when integrating them into a system. Concerning robotics requirement criteria and the proposed objectives of this research, geared drive motors meet most of them on a moderate or high level.

Their biggest disadvantages are cost and size, improving in those aspects is the industry's current focus, coming up with new compact designs at the lowest cost possible without giving up on mechanical strength.

Table 1: Actuators Analysis, reproduced from [20].

ACTUATOR TYPE	SPEED	TORQUE	COST	PRECISION	ENERGY EFFICIENCY
Geared Drive Motor	Moderate to High	Moderate to High (with gears)	Moderate to High	Moderate	High
Direct Drive Motor	Low to High	Low	High	High	High
Hydraulic Actuator	Low to High	High	High	High	Moderate
Pneumatic Actuator	Moderate to High	Low	Low to Moderate	Low	Low

Furthermore, there are different styles of robot actuator joints: the compact intergraded actuator joint units with housing, a separate system that can be entirely mounted on the robot's link or the integrated robot arm joints that use the robot's link or a section of it as the housing itself for all the actuator components. Commercial actuator robot joints tend to be the first style, giving all the components integrated within a housing that can have different shapes and installation features. Ranging from simple shapes like a cylinder as in the eRob I series [21] or a rectangular prism as in the Robotis DYNAMIXEL-P series [22] which can be positioned inside the robot's link, up to a 90-degree angled section like a T connection joint with the robot's link as in the eRob T series [23] these are designed with the intention of offering a "plug and play" experience. On the other hand, the second style is mainly used in entirely custom projects, where a designer can purchase all the components separately and install them directly in the robot's link. These require more precise manufacturing procedures of the link to keep the necessary offsets between components such as frameless motors, harmonic drives, and more. This approach can take a longer time to develop the project, but it can offer more control over the final result if done correctly by an expert and can also represent more flexibility in the positioning of components along the links. A clear example of this is the model LWR III [13].

Although both approaches can give good results, the final path will depend on the designer's time frame, objectives, resources, and expertise. However, it is important to consider that the designer can focus solely on the arm's design by using integrated actuator units; this can lead to more time exploring other factors that influence the robot's performance, like link length, position of the actuators, link shape, and more factors that can help move forward the power wheelchair mounted assistive robot arm's industry.

1.3 Proposed Solution

The presented research offers a comprehensive methodology for robotic actuator design and shows all the essential considerations that are key to achieving the desired performance.

Also, this research seeks to present the design and development of a robot joint actuator that covers the needs of assistive robot arm development, pushing forward the design of assistive robot arms. The proposed integrated actuator robot joint strongly seeks to be physically compact, small, lightweight, hollow, and easy to control and install without sacrificing mechanical strength.

The specific aims of this research are:

Aim-1: Design and Development of Custom-Designed Actuators for Assistive Robot Joints.

Aim-2: Testing and Evaluation of Integrated Robotic Actuators.

Aim-3: Exploration of the Benefits of Custom-Designed Actuators in a 6-DOF Robotic Manipulator.

1.4 Structure of the Thesis

To meet the proposed aims, this research is structured into chapters as follows:

Chapter 2: Literature Review

This chapter covers all the theoretical knowledge necessary to accomplish the proposed aims, starting with a review of design methodologies to choose the most appropriate one in this context. Followed by a comprehensive review of assistive robot arms, assistive robot arm actuator joints, the usual components of actuator's robotic joints as well as their proper selection, classification, and more. Components like motors, transmission systems, joint mechanisms, sensors, controllers, drivers, brakes, mechanical stops, and mechanical structures. To finish with the exploration of how to integrate robot joint actuators into robot arms systems.

Chapter 3: 6-DOFs Wheelchair Mounted Assistive Robot Arm at UWM Bio-Robotics Laboratory

This chapter established the basis of an existing wheelchair mounted assistive robot design, detailing its characteristics and identifying areas for improvement. It focused on reducing the system's total weight and size.

Chapter 4: Design And Development of Custom Actuators for Robot Joints

This chapter offers a path of design, presenting first the design methodology approach taken and its justification, followed by the clear steps to a hybrid/mixed design methodology that takes the most relevant features of the multiple design methodologies presented in Chapter 2. Continuing with the application of the steps to the design and development of custom-designed integrated actuators for assistive robot arms, presenting the design goals and requirements, components selection, and their constraints. The chapter closes by presenting the CAD model design, materials selection, manufacturing process, and prototyping.

Chapter 5: Testing Experiments, Results and Discussions

This chapter focuses on testing the custom-integrated robotic actuators, evaluating their performance, and characterizing the design. It also walks through the testing procedure, setup, and installation requirements for using the actuator in any robot arm design.

Chapter 6: Exploration of the Benefits of Custom-Designed Actuators in a 6-DOF Robotic Manipulator.

This chapter presents a comparative analysis of weight reduction and dimensional improvement in an existing 6-DOF manipulator design, redesigning it with custom-integrated actuators for robot joints.

Chapter 7: Conclusion and Future Works.

This chapter presents a condensed review of the research outcomes, highlights, and future works.

1.5 Contribution

As a result of this research, the proposed integrated actuator for robot joints is shorter and lighter than the comparable options on the market. It comprises an EC motor, a holding brake, and a harmonic drive. Also, the design features the following installation characteristics: it is hollow in the center of the assembly, the housing incorporates two rings with threaded holes to choose the necessary fixing points that adapt best, the traditional gear mounting points for the output shaft, and external threaded mounting points for the controller of the motor.

These characteristics bring the following benefits to robot assistive robot arm design:

Considering physical design and installation, it improves compactness as the actuators in the assembly take up less volume, cables can pass through it, and the different mounting points enhance the integration of the design with other systems. There are also more possible orientations that securely attach the actuator, reducing the number of parts needed to install it.

On the other hand, considering the performance of robot arms improves energy efficiency and battery life and increases payload capacity by reducing the overall weight. Also, the incorporated brake offers a safety measure while maintaining the accuracy and control required for this application.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical Development of Wheelchair-mounted Assistive Robot Arms

Assistive robot arms aim to help the user complete tasks that involve picking, placing, opening, closing, and holding objects [4], the activities of daily living (ADLs). The first model proposed was the KARES I in 1999, designed by the Korean Advanced Institute of Science and Technology (KAIST) [24]. Since then, new designs and iterations have been proposed, as shown in Table 2.

Table 2: DOFs and Control Tools of Assistive Robot Arms.

MODEL	Year	DOF	Purpose	Precursor	control	Source
KARES I	1999	6	ADL assistance	x	Keyboard / voice	[24]
MANUS	2000	6	ADL assistance	x	Keyboard / Joystick	[25]
Weston	2002	6	ADL assistance	x	Joystick	[26]
KARES II	2003	6	ADL assistance	KARES I	vision / sensory glove / electromyographic (EMG) signal	[27]
FRIEND I	2003	7	ADL assistance	MANUS	--	[28]
DLR LWR III	2003	7	ADL assistance	DLR LWR I & II	--	[14]
FRIEND II	2005	7	ADL assistance	AMTEC	Electroencephalography	[28]
WRMA I	2005	7	ADL assistance	x	Joystick	[11]
WRMA II	2008	7	ADL assistance	WRMA I	Joystick	[12]

JACO	2009	6	ADL assistance	x	Joystick	[16]
FRIEND III	2009	7	ADL assistance	LWA3 by Schunk	--	[28] [29]
iARM	2012	6	ADL assistance	MANUS	Joystick / keyboard / a button	[17]
FRIEND IV	2012	7	ADL assistance	FRIEND III	Chin joystick / Head control interface	[30] [15]
Kinova Gen 2	2013	6	Cobot	JACO	--	[31]
Kinova Gen 2	2013	7	Cobot	JACO	--	[31]
EDAN (DLR LWR III)	2016	7	ADL assistance	DLR LWR III	Joystick / electromyographic signals	[14] [15]
Kinova GEN 3	2018	7	Cobot	Kinova Gen 2	--	[32]
Kinova GEN 3	2018	6	Cobot	Kinova Gen 2	--	[32]
Kinova Gen 3 lite	2019	6	Education	Kinova GEN 3	--	[33]
BATEO	2019	6	ADL assistance	x	Joystick	[18]
mR2A	2023	6	ADL assistance	x	Joystick / keyboard	[15]
Pick&Eat	2024	5	Meal assistance	x	Ultrasonic sensor	[34]

Note: Information missing from publications and available documents has been marked as “--”.

Their general characteristics, such as the DOFs and user control methods, are usually mentioned, but the information available tends to omit specific details on the hardware used. In cases where the focus is on improving previous designs, the primary point shifts to using or developing better hardware and more inclusive control methods. Also, the wiring handling got better with time, resulting in models with inner wiring, creating the need for hollow integrated actuator joints.

There is a clear trend of basing new models on previous ones. The early research development of the MANUS model in 2000 was used in the first version of the FRIEND system and set the basis for creating the iARM in 2012, which is commercially available. With time, most of the research has evolved into companies or products.

Furthermore, the development of the JACO arm [16] from Kinova, commercially available since 2009, has derived into the Gen 2 [31], 3 [32], and 3 lite [33] designs, which are cobots that still have the appropriate characteristics of wheelchair-mounted assistive robot arms. A lightweight system is vital to compatibility with different power wheelchairs' payload capacities. Some standard points of comparison between the robot arms can be their DOFs, payload capacity, reach, weight, and control method, as shown in Table 3 (see next page). This compilation allows for a better understanding of the current state of this technology; there are more unique and specific features not mentioned in the table, like the addition of cameras in the wrist joint in some of the models like FRIEND III and Kinova Gen 3.

Table 3: Robot Arms Main Characteristics.

MODEL	DOF	Reach (m)	Total Length (m)	Payload (Kg)	Arm weight (Kg)	Payload-to-weight
KARES I	6	0.82	--	0.5	22.9	0.02
MANUS	6	0.8	1.05	2	13	0.15
Weston	6	1.2	--	--	--	--
KARES II	6	--	--	2.3	--	--
FRIEND I	7	--	--	--	--	--
DLR LWR III	7	0.936	--	14	14	1.00
FRIEND II	7	--	--	--	--	--
WRMA I	7	1.245	1.37	6	12.5	0.48
WRMA II	7		1.1	4	11.5	0.35
JACO	6	0.9	1.1	1.3	5.2	0.25
		0.45		1.6		0.31
FRIEND III	7	--	1.0762	5	--	--
iARM	6	0.9	--	1.5	9	0.17
FRIEND IV	7	--	--	--	--	--

Kinova Gen 2	6	0.985	--	1.3	5.2	0.25
		0.4925	--	1.6		0.31
Kinova Gen 2	7	0.985	--	1.1	6.18	0.18
		0.4925	--	1.4		0.23
EDAN (DLR LWR III)	7	--	--	1	--	--
Kinova GEN 3	7	0.92	--	2	8.2	0.24
		0.46	--	4		0.49
Kinova GEN 3	6	0.891	--	2	7.2	0.28
		0.4455	--	4		0.56
Kinova Gen 3 lite	6	0.76	--	0.5	5.4	0.09
BATEO	6	0.9	1	1	5	0.20
mR2A	6	1.183	1.25		13	
		1.08		3		0.23
Pick&Eat	5	--	0.7	0.1	1	0.10

Note: Information missing from publications and available documents has been marked as “--”.

2.1.1 5-DOFs Assistive Robot Arms

One approach to reducing the overall weight of this type of assistive robot arm is by reducing the number of DOFs; for ADL assistance, this is a big challenge, and they are mainly kept at 6 DOFs minimum to ensure maneuverability. The DOF can be reduced more once the tasks are reduced to only meal assistance. From the studies that developed the Pick&Eat model, it was found that 5 DOFs were appropriated [34]. Although there are more meal assistant options in the market, their approach resembles ADLs wheelchair-mounted robot arm assistants.

2.1.2 6-DOFs Assistive Robot Arms

For the 6 DOF arms in Table 3, the models' maximum reach ranges from 0.76 m to 1.2 m, and payload ranges from 0.5 to 4 kg, considering that the 4 kg load is at 0.4 m distance, Kinova Gen 3, and the second largest is 3 kg at 1.08 m, mR2A, which shows an actual higher capacity. The models at 0.5 kg payload are KARES I and Kinova Gen 3 Lite, designed for education purposes. Their weight ranges from 5 kg to 22.9 kg, being BATEO the lightest with a reach of 0.9 m and payload of 1kg. Although the heaviest is KARES I at 22.9 kg, and at the minimum payload capacity of 0.5 at a 0.82 m distance, this model was one of the first in this application field. Furthermore, the payload-to-weight ratio is 0.02 to 0.56. Considering that 0.56 is at a 0.4 m distance, Kinova Gen 3, the highest of interest is 0.28, Kinova Gen 3, with a maximum reach of 0.89, a payload of 2 kg, and a weight of 7.2 kg.

2.1.3 7-DOFs Assistive Robot Arms

For the 7 DOF arms in Table 3, the models' maximum reach ranges from 0.92 m to 1.245 m, and payload capacity ranges from 1 to 14 kg, considering that the 14 kg load is at 0.9 m distance, DLR LWR III. The 1 kg and 1.1 kg payload models are EDAN, developed based on the DLR LWR III and Kinova Gen 2, a Cobot. The 7 DOFs arm’s weight ranges from 6.18 kg to 14 kg; Kinova Gen 2 is the lightest, with a reach of 0.98 m, and the heaviest is DLR LWR III, 14 kg, it is also the model with the highest payload capacity of all the information collected at 14 kg, with Payload-to-weight ratio of 1, also the highest of all. Furthermore, the 7 DOFs arms' payload-to-weight ratio ranges from 0.18 to 1, with a minimum of 0.18, corresponding to the Kinova Gen 2 model.

2.2 Wheelchair-mounted Assistive Robot Arms and Their Design Requirements

The design considerations of assistive robot arms are directly related to the characteristics of power wheelchairs, which significantly impact the design decision for their integrated actuator robotic joints. The usual design goals for wheelchair-mounted assistive robot arms are manipulability, greater payload, effortless control, reconfigurable, as light as possible, and side mounting [35], as well as high payload-to-weight ratio, hollow structure, modular, human appearance, safe collaboration, high precision, robust design, and compliance [36].

2.2.1 Assistive robot Arms DOFs and Link length

Assistive robot arm design is usually initially based on the actual human arm, which has 7 DOFs but requires only 6 DOFs to position and orient the hand. This characteristic implies that multiple configurations, paths, or solutions exist to get to the desired point in the space [37]. As a point of reference, the human arms span of a large operator from norm ISO3411 is 1.942 m (76.46 in), and the head breath distance of 0.163m (6.42 in) [38], we can consider that the distance from the clavicle to the tip of the fingers is half the difference between the two previous values, 0.889m (35.02 in). Also, most assistive robot arms are closer to this value, like the JACO, iARM, and EDAN, with a reach of around 0.9 m. However, there is a distinction between the reach and total length of the robot arm. In the case of JACO, the total length is 1.1 m, as it has a 0.2 m lift unit, plus the rest of the arm of 0.9 m, considered the reach.

Studies on link length optimizations have shown that longer arms do not guarantee better performance, as they could generate heavier systems [39] and, therefore, require higher torques to hold themselves. A balance between needed reach, power consumption, target payload, hardware constraints on link length space, the theoretical weight of the links, the shape of the joints that can limit the actuator's angles, DOFs, and other factors needs to be considered. On [40], an objective function was proposed, and it can be personalized to each design case's needs considering a target workspace.

2.2.2 Activities of Daily Living (ADLs) Workspace

On the design of wheelchair-mounted assistive robot arms, the ADLs volume dimensions define the ideal robot arm’s workspace, considering the Lawton Instrumental ADLs (IADL) scale and Briston ADLs scale [41]; through customer discovery research, a volume of 48 inches (1.22 m) from the floor to a top shelf area, by a depth of 20 inches (0.51 m), by a width of 66 inches (1.68 m) was defined as the workspace for the tasks outside of the immediate nearby space of the user [42]. Also, the volume for tasks like eating, drinking, or talking on the phone was approximately 17 inches (0.43 m) in height, 26 inches (0.66 m) in width, and 8 inches in depth, considering the placement of 29 inches (0.74 m) from the floor to the bottom of the space [42], the other dimensions depend on the specific placement of the robot arm and the user. Still, an offset of 6 inches (0.15 m) was considered from the back of the chair to the back of the volume [42]. Also, identifying the objects present in these spaces allows us to assess the heaviest object that the robot arm could encounter within the ADLs and the corresponding distance from the origin of the robot arm. This can be set as the desired payload capacity of the robot arm at a determined distance; the payload capacity of the robot arm as its full extension may not reflect the robot arm's capabilities at shorter distances. Also, the gripper, end-effector, or tool attached to the wrist of the robot must be capable of handling the loads. The weight of these objects ranges from 1 gram to 4 kilograms [43]. As some products come in different sizes, not reaching the goal of 4kg is not necessarily a complete limitation. For example, having access to milk, a gallon weighs 3.90 kg, a liter weighs 1.03kg, a quart weighs 0.95 kg, and so on.

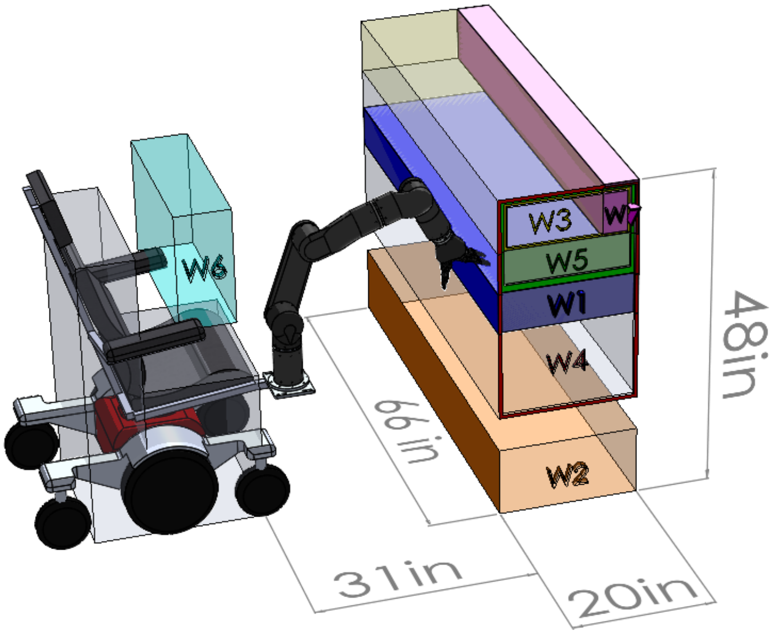


Figure 1: ADLs workspace, in compliance with ADA, image reproduced from [42].

2.2.3 Robot Arm System Allowable Weight

Physical characteristics directly influence performance; the system's overall weight is critical in this design as one of the factors that affect the power consumption of the wheelchair is the load that it is carrying. Mounted on the wheelchair, the robot arm takes away part of the wheelchair's payload capacity, assigned to carry a user and other objects that can be held or manipulated safely over it. Also, the wheelchair's energy consumption is proportional to the payload capacity in use; therefore, this system needs to be as light as possible to interfere in the least. To select a power wheelchair, it is recommended to follow the advice of a professional, but Medicare Coverage considers 95% of the wheelchair’s payload as the maximum weight of the user [44], leaving a 5%

capacity that can be used for other loads, such as the robot arm system and the objects being handled. See Table 4 for wheelchair capacity values and Table 5 for payload considerations.

Table 4: Power Wheelchair Payload Capacity reference values.

	Payload Capacity		
Power Wheelchair	**Min. (lb.)**	**Max. (lb.)**	**Source**
Pediatric	--	125	[44]
Standard Duty	250	300	[45], [44]
Heavy Duty	301	450	[44]
Very Heavy Duty	451	600	[44]
Extra Heavy Duty	601	700	[44], [45]

Table 5: Wheelchair Payload Capacity, 4kg load consideration.

	Payload Capacity				**Payload Capacity**			
	95%	**5%**		**load**	**--**	**Max - Min**		**Load**
	User	**R. Arm + Load**		**4 (kg)**	**User**	**R. Arm + Load**		**4 (kg)**
Power Wheelchair	**Max (lb)**	**(lb)**	**(kg)**	**R. Arm (kg)**	**Min. (lb)**	**(lb)**	**(kg)**	**R. Arm (kg)**
Pediatric	118.75	6.25	2.83	--	--	--	--	--
Standard Duty	285	15	6.80	2.80	250	50	22.68	18.68
Heavy Duty	427.50	22.5	10.20	6.20	301	149	67.57	63.57
Very Heavy Duty	570	30	13.61	9.61	451	149	67.57	63.57
Extra Heavy Duty	665	35	15.87	11.87	601	99	44.90	40.90

From Table 5, the most critical scenario is a standard-duty power wheelchair carrying a load of 4kg with a mounted robot arm system with a maximum mass of 2.8 kg, which sets the bar to a payload-to-weight ratio of 1.43. Also, in the case of pediatric wheelchairs, as the remaining 5%

payload capacity is 2.83 kg, a reconsideration of the maximum mass of the object should be made, and could be handling objects of medium weight, with a maximum of 1kg [43], if so, the maximum load of the robot arm system can be 1.8 kg. The remaining three scenarios are achievable depending on the location of the maximum load of 4kg or the reach of the robot arm.

2.2.4 Americans with Disabilities Act (ADA) standard and Robot Arm System Possible width

Furthermore, the dimensional specifications of the power wheelchair and the architectural standards considered in the Americans with Disabilities Act (ADA) can be used to determine the clearance space or the maximum width a robot arm can occupy when mounted on a power wheelchair without colliding with structures, allowing the user to pass through doors and corridors without inconvenience. Therefore, the minimum clear width of general corridors and doors is 36 inches (0.91 m), and the exceptions accept a reduced width of 32 inches (0.81 m) [46]. Also, the overall width of power wheelchairs is a minimum of 24 inches (0.61 m) (Standard models) [46] and a maximum of 29.25 inches (0.74 m) (Bariatric models) [47], like the "Jazzy 1450 Bariatric Power Wheelchair-600 Lbs. Capacity". Considering these values, the minimum total clearance is 2.75 inches (6.9 cm) for a bariatric model and a 32-inch narrow door and a total clearance of 6.75 inches (17.1 cm) for a 36-inch standard door. It is essential to note that the ADA only mentions the standard models with a maximum wheelchair width of 27 inches. Therefore, the minimum total clearance they have considered is 5 inches (12.7 cm). To respect the ADA consideration, the robot arm system should specify the compatible types of wheelchairs, considering their placement over it. Only wheelchairs with a width of less than 27 inches can use the free space to accommodate the complete robot arm system or a section of the design. Also, an analysis of the clear space available within the overall width of the wheelchair and the width of the seat on one side needs to be made and can have, if necessary, a specified offset from one side of the wheelchair seat. This space can be used and added to the maximum width of the robot arm system.

$$Rw = Dw - \frac{Ww - Ws}{2} - Tc - \; oDo \tag{2.1}$$

In this equation Rw is the Robot Arm System Width, Dw is Door Width, Ww is Overall Wheelchair Width, Sw is Wheelchair Seat width, Tc is Total clearance, and oDo is the Optional design offset. Now, consider a standard 36-inch door, a standard maximum width of 27 inches, a wheelchair seat of 20 inches, a total clearance of 5 inches, and a design decision of an optional offset of 1.5 inches. We get a maximum width of the robot arm system equal to 6 inches (0.15 m), as shown in **Figure 2**., see next page.

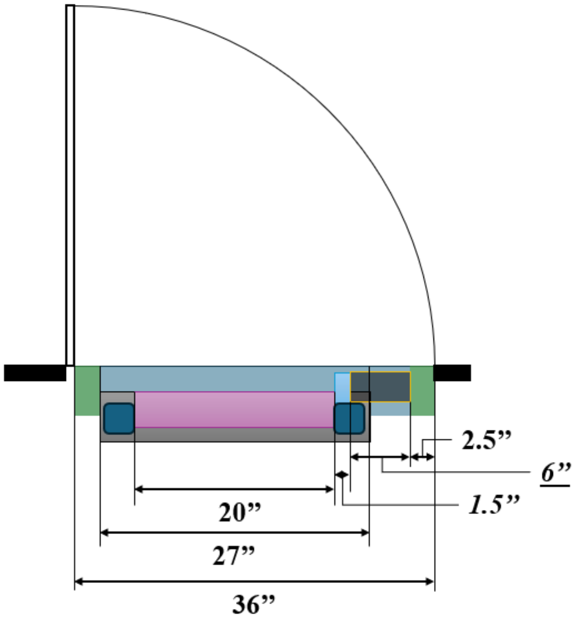


Figure 2: Robot Arm system maximum width with standard conditions

Robot arms placed inside the wheelchair's width limits will not be at risk of colliding, but considering **Equation 2.1**, the available data on power wheelchair dimensions, presented in Table 6, and the available door size accepted by the ADA presented in Table 7 , we get the possible robot arm width range also presented in Table 7.

Table 6: Power Wheelchair Width, Seat Width, and clearance considerations.

Electric Wheelchair	**Overall Width (in)**		**Seat width (in)**		
	Min	Max	Min	Max	Source
Standard	24	27	16	20	[47]
Foldable (Travel)	22.5	22.5	16	18	[47]
Bariatric	24.25	29.25	20	24	[47]

Table 7: ADA Door Sizes and possible robot Arm Width Range.

	IBC and ADA standard rule, Door Width (in)									
	32		**36**		**41.5**		**42**		**48**	
Electric Wheelchair	**Robot Arm System Possible Width Range, considering both min or max of Table 6**									
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Standard	5.5	2	9.5	6	15	11.5	15.5	12	21.5	18
Foldable (Travel)	6.25	5.25	10.3	9.25	15.75	14.8	16.3	15.3	22.3	21.25
Bariatric	3.38	-1.1	7.38	2.88	12.88	8.38	13.4	8.88	19.4	14.88

The data on the possible sizes of robot arm systems depending on the type of wheelchair show that even though the table shows a 32-inch door, there are narrower options in the market, like interior bifold door panels of 24, 28, and 30 inches, that were not considered in the calculations as they can use two panels to create one doorway or utilized for closets.

Table 7 shows some critical design values, such as 2 inches. This one is challenging, considering the narrowest door with the maximum width of a standard power wheelchair. Special design considerations could be made to achieve it. Some values, like the optional offset, can be modified for this case. Considerations of the turning radius of the power wheelchair model to be sure of its maneuverability, the desired payload capacity of the design can also be reconsidered to align with the size of the available actuator joints in the market or explore different torque transmission mechanisms, the hardware size is a limitation that usually pushes to customize an entire specific solution, as the dimensions of an actuator increase with its torque capacity. Miniaturization aims to solve this issue.

The usual positioning for these robot arms is at one side, left or right, and in the front area of the power wheelchair, as it allows for more workspace coverage [12]. All assistive rotor arms have this characteristic; even the WESTON model, proposed by the Bath Institute of Medical Engineering in 2002, is unique in this category, as it is a modified SCARA-type robot arm. All its joints operate in a horizontal plane except for one vertical actuator [26], this gives it an advance in performance on upper shelf grasping of objects as it can situate the entire robot parallel to the working plane and is only limited by its height. The other proposed designs are jointed-arm types of robots with fixed lift sections, usually the base or first link of the arm.

For a more specific placement, an optimization considering the best possible coverage of the workspace should be made considering the specifications of each case of the power wheelchair and robot arm, as it was presented in [48] for a standard power wheelchair using the xArm robot.

The 5-inch total clearance recommended by the ADA should also be considered when determining the base placement.

2.3 Robot Arms as Mechatronic Serial-link Mechanisms

Robot arms are serial-link mechanisms and can be described using the Denavit-Hartenberg (DH) parameters [49], detailing the DOFs, joints, link length, and possible joint angles. These systems are generally composed of five main components: actuators, which generate movement and provide the torque and speed of the robot; structural links, which are the housing of all internal components and provide the stiffness necessary to transmit the torque through the system; sensors, which detect the changes in the system of position, velocity, temperature, torque, or more and transmit the signals; Digital I/O and controller, which together ensure the communication between all the devices in the system, the first one receives and sent electrical signals and the second one received, compare and transmit the appropriate decisions or commands to the system; and finally, the power source which provides the necessary electrical energy to run all the system.

Also, wires and connectors are required for electrical connections and communications. Planning their handling can help ensure the integrity of the design and its aesthetics. Hollow actuators can help guide the cables through the link's interior. If improperly protected, exterior cables could become a hazard. To use this approach, most system components need to be hollow or smaller than the inside cavity of the link to leave a width with enough clearance to pass all electrical connections. Usually, there will be one actuator per DOF since the communication between all electrical devices is a chain, and these actuators are positioned inside each link. This implies the need for an electrical tree-type connection, as shown on **Figure 3**. These electrical connections generally comprise power, ground, and signal wires that branch out from the principal path.

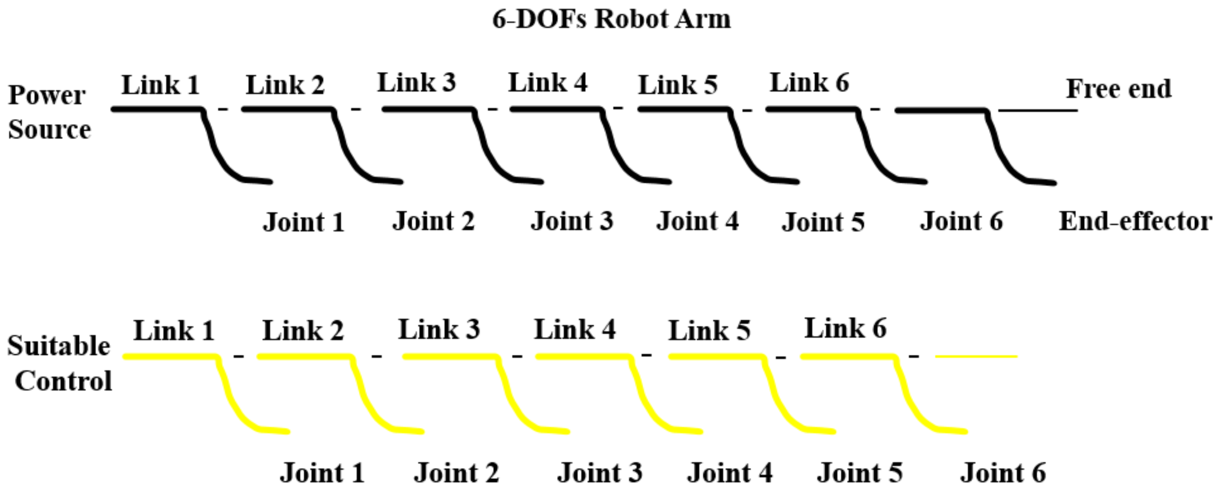


Figure 3: Tree-type electrical connection of a 6-DOFs robot arm.

Considering the system components, the joint in this context groups the actuator, sensors, digital I/O, controller, and any other electromechanical component like electromagnetic brakes, which are a possible safety feature of the system. Also, these joints are punctual loads along the structural links, and their mass highly influences the total weight of the robot arm. Thus, the challenge of creating light intergraded actuator robot joints without sacrificing their individual torque capacity.

Since these robot arms are usually for a general purpose, they are designed with 6 or 7 DOFs, occasionally with 8 DOFs [15]. The 6-DOF JACO robot arm, weighing 5.2 kg, is currently the lightest among its peers, with a payload of 1 kg at its total reach of 0.9 m [16]. For specific applications like meal assistance, the DOFs can be reduced to 4 or 5 [34]. For example, the Pick & Eat robot arm of 5DOF, which weighs 1kg, its payload capacity is 0.1kg, and its total reach is 0.7 m [34].

2.3.1 Wheelchair-mounted Assistive Robot Arm's joints

At the early stages of every new technology, there are times when no commercial solution is available that satisfies all the design requirements; thus, the engineer analyses the viable partial solutions and customs the final one based on their integration. Once the market recognizes the new needs, specialized companies tend to step in and offer new integrated solutions. Robot joints are not the exception to this; the early designs used the current partial solutions and designed around them, resulting in structural links that house all the components of the joint, requiring rigorous manufacturing and mounting processes, respecting the needs of each element, and taking longer time to complete their developments. Nowadays, this design step could be skipped by installing an integrated actuator unit inside the link, leaving behind the complexity of integrating the components. The time and energy saved can be invested in optimizing and innovating other aspects of the robot arm, like the link structures and control strategies.

One of the most renowned electric drive companies, Maxon, has solutions that can be adopted for both cases: frameless motor kits to personalize the most appropriate solution and the ready-to-install high-performance joint (HPJ) [50]. Even so, there is room for size, weight, and installation improvement.

2.3.2 Actuator Joints used in wheelchair-mounted assistive robot arms

One of the assistive robot arms with the most detailed development of its integrated actuator joint is the LWR III. The Lightweight Robot III (LWR III), developed by the German Aerospace Center (DLR), puts its innovative joint design front and center, making it a standout in robotic arm technology. Each of its seven revolute joints is an intelligent, self-contained module, integrating actuators, electronics, and sensors in a way that mimics the flexibility and precision of a human arm [13]. A motor, a gear unit, sensors, a power supply unit, a controller, and a power converter integrate the joints [13]. These joints have advanced sensors, including motor and link-side position sensors, as well as a torque sensor that is important to the arm's performance, as it allows it to stabilize itself actively, ensuring it remains safe and responsive when interacting with humans or navigating unpredictable environments. Joints are seamlessly connected through streamlined power and communication lines, an emergency loop circuit, and an optical SERCOS bus for fast and reliable data transfer [13]. The lightweight yet strong carbon fiber composite link ties it together, ensuring the arm remains agile without compromising durability [13].

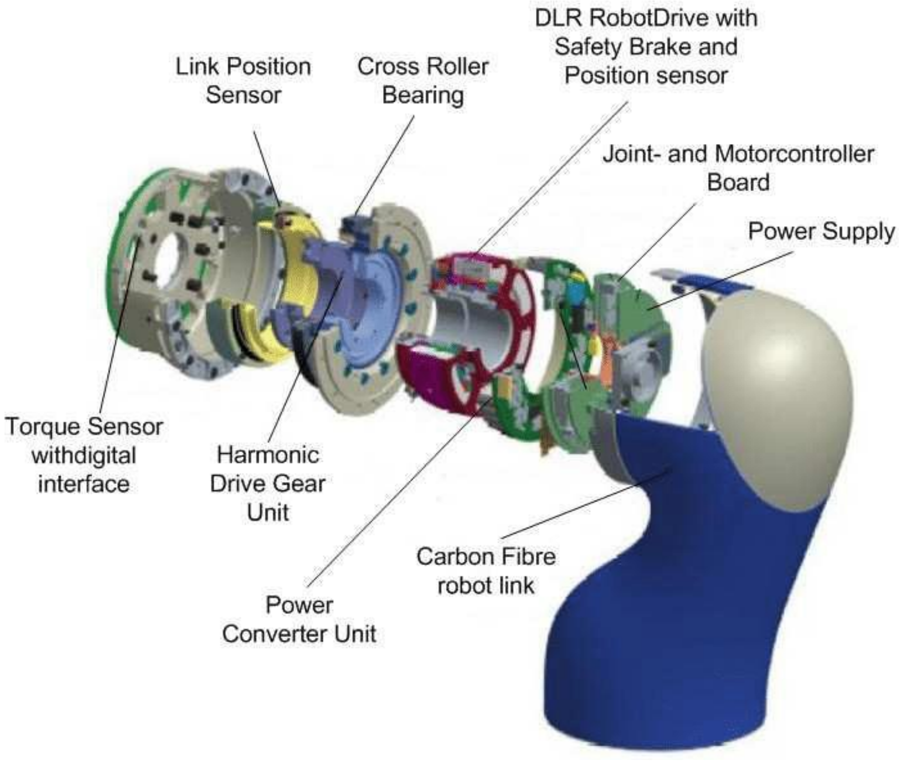


Figure 4: Integrated actuator joint of the LWR III. Reproduced from [13].

The LWR III is the heaviest model, considered one of the lightest, at 14 kg. The next model, with 13 kg, is the mR2A. This model uses commercial integrated actuators, the QRob series with brakes, friction damping brakes, an encoder, 19/20bit resolution, and EtherCAT communication [15]. The motor’s nominal toque used ranged from 52 to 5.4 Nm, QRob 90 with 52 Nm, QRob 80 with 31 Nm, QRob 70 with 10 Nm and QRob 70h with 5.4 Nm. The use of actuators with higher torque implies adding more weight to the system but also improving the payload capability.

On the other hand, Kinova's JACO robot arm uses a basic joint. It incorporates a brushless DC motor [50] with a gear unit. The motor has incorporated position encoders, accelerometers, torque, temperature, and current sensors. Kinova nomenclature for their actuators is: Joints 1 & 3: K-75 actuators, Joint 2: K-75+ actuator, Wrist: K-58 actuator [16]. Their characteristics can be found in Table 8 and seen.

Figure 5: Kinova actuators: K-75+, K-75 and K-58.

Table 8: Kinova actuators specifications, K-75+, K-75, K-58. Reproduced from [51].

Title	K-75+	K-75	K-58
Nominal Torque (Nm)	12	9.2	3.6
Peak Torque (Nm)	30.5	18	6.8
No load speed (rpm)	12.2	9.8	20.3
Nominal speed (rpm)	9.4	7	15
weight (g)	570	587	357
Reduction ratio	136	160	110
Angular ranges, software limited (turns)	± 27.7		
Communication protocol	RS485		

Furthermore, in the case of the FRIEND project, Schunk was one of the developer partners of the Institute of Automation (IAT) of the University of Bremen. Thus, Schunk's PRL servo-electric rotary actuator series, a commercial integrated actuator module, was used [52]. Their characteristics can be found in Table 9; it is worth noting their weight. Also, a model can be seen in Figure 6.

Figure 6: SCHUNK: Universal Rotary Actuator PRL. Reproduced from [53].

Table 9: SCHUNK: PRL series, sizes 60, 80, 100, 120. Reproduced from [53].

Type	**60**	**80**	**100**	**120**
Nominal Torque (Nm)	4.5	20.7	81.5	216
Peak Torque (Nm)	9.6	41.4	175	372
weight (kg)	1	1.2	2	3.6
Hollow shaft diameter (mm)	8	12	13	18
length	102	112.5	134	156
Diameter (mm)	77	90	112	132
section outside the diameter (mm)	4.6	3.9	- -	- -
Motor Type	Brushless DC servo motor			
Holding brake	Integrated			
Reduction ratio	300:1	552:1	625:1	596:1
Sensor system	Incremental encoder with absolute encoder function			
Interfaces	RS-232; Profibus-DP; CAN-Bus			

2.3.3 Relevant Specific Components

Robot joint components consider the following: movement and toque generation, increment and transmission of torque, detection of changes in the system, safety features, communication protocols, and control. The aim of light, slim, and compact joints pushes designers to use electric actuator options, which tend to have a size proportional to their toque capacity. Smaller motors give smaller torques than bigger ones. To overcome this, geared mechanisms like harmonic drives are added to increase the output torque, help promote a smooth movement of the system, and, depending on the model, prevent backslash. Usually, their use requires a connection output torque shaft that can directly be connected to the following link of the robot arm. Also, as a safety feature for assistive robot arms, a brake can be added directly to the actuator's shaft to help hold loads and position like small electromagnetic friction brakes. Furthermore, capturing data on velocity, temperature, position, and torque requires the integration of sensors. Depending on the actuator, most of these sensors will be already integrated into it to facilitate its control. The output torque of the joint can be theoretically calculated with a certain tolerance based on the information provided by the motor's sensors. In case of a high precision requirement or if the actuator does not integrate them, an absolute encoder, hall sensor, and toque sensor can be added to the system. A compatible driver is added to ensure communication and control between all electromechanical components; a good driver can handle all components and communicate with the following robotic actuator joint. The communication protocol can also influence performance and set the required wiring specifications.

2.3.4 Current Commercially Available Robotic Actuator Joints

Multiple companies have presented compact actuators to the market for robot joints and generic joints that aim to be used on robot arm designs, such as Maxon Group (Automation company) [50] and more, like Rozum servomotor RDrive [54], Igus ReBeL actuator [55], Nikon Motion Motors with the C3 eMotion series [56], ZeroErr (ZeroErr Control Co.,Ltd) [57], [21], and TINSMITH (Zhengzhou Defy Mechanical&Electrical Equipment Co. Ltd.) [58] with eRob Rotary Actuators series, Laifual with high voltage rotary actuators MIS series [59], ROBOTIS power by DYNAMIXEL with DYNAMIXEL-P series [60], [22] and DYNAMIXEL-Y series [61], [62], Sierramotion, an Allied Motion Company with the SMRT-2000 Robot Joint series [63], Roboct with robot joint modules [64], TONIFISHI with the HJ [65] and PH [66] series, Sumitomo Drive technologies with TUAKA series [67]. Although many products have been launched and are available to the public, there is still room for improvements and designs that respond to the specific needs of electric wheelchair-mounted assistive robotic arms. An evaluation of the presence of the critical components of the robot joint is made in **Table 10**. Where X indicates the presence of the component in the actuator. From this, it can be concluded that the Maxon HPJ-DT and Erob series are the most complete solutions, closely followed by the C3 eMotion. As mentioned before, the presence of brakes and a hollow shaft is strongly preferable.

Table 10: Comparison of commercially available actuators and their components.

		Components Present							Note	
Brand	**Model**	**EC Motor**	**Controller**	**Harmonic gear box**	**Encoder (Qty)**		**Brake**	**Torque Sensor**	**Backlash**	**Hollow feature**
MAXON	HPJ-RJ	X	X	X	X	2	X	X	No Backlash	X
ZeroErr **TINSMITH**	Erob	X	X	X	X	2	X	X		X
Nikon	C3 eMotion	X	X	X	X	2	X			X
Laifual	MIS	X	--	X	X	1	X			X
Sumitomo Drive Technologies	TUAKA	X	X	X	X	1	X			X
MAXON	HPJ-DT	X	X	X	X	2		X	No Backlash	X
Rozum	Rdrive	X	X	X	X	2			Almost-zero backlash	X
TONIFISHI	PH	X	X	X	X	2	X			X
		X		X	X	1				X
	HJ	X	X	X	X	1				X
Robotis / DYNAMIXEL	DYNAMIXEL-Y	X	X	X	X	1	X			X
	DYNAMIXEL-P	X	X	X	X	2				
Sierramotion, an Allied Motion Company	SMRT-2000 Robot Joint	X	X	X						X
Roboct	robot joint modules	X	X	X	X	1		X		

The two highest options are analyzed below: the Maxon HPJ-RJ and the Erob model.

2.3.4.1 MAXON: HPJ – DT and RJ series

Maxon offers the HPJ–DT series without a break, see Figure 7, and the HPJ-RJ series, see Figure 8, with a brake as integrated actuators suitable for robot arms. The torque ranges respectably are from 12 Nm to 484 Nm and from 5 Nm to 350 Nm [68]. Adding brakes to the system can considerably increase its weight, as the RJ series is heavier than the DT. A system of 1.8 kg from the DT series (DT50M-WGU20) can output a peak torque of 73 Nm – 120 Nm, more torque than the RJ 60 with a peak torque range of 25 Nm – 65 Nm [68], see **Table 11** and **Table 12**. For wheelchair-mounted assistive robot arms, actuators with brakes are an essential safety measure that can help the robot arm keep its position while holding itself a load, or in case of an energy shortage, it will not suddenly fall; also, as an emergency stop.

Even though the HPJ -RJ Series is more complete, it still has more mass and considerable size than other offers in the market. The high quality of MAXON control and its craftmanship undoubtedly make it one of the strongest options, but it is still not ideal.

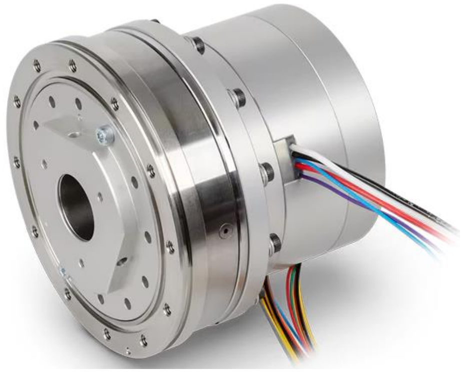


Figure 7: MAXON: HPJ – DT Series. Image reproduced from [68].

Table 11: MAXON: HPJ - DT series, relevant values. reproduced from [68].

HPJ-DT series (Hollow shaft, No brake), System	Peak Joint Torque, Repetitive	Peak Joint Velocity	Mass	Outer Dia
DT38S-WGA14	12 Nm – 19 Nm	8.9 rad/s – 17.8 rad/s	0.9 kg	74 mm
DT38M-WGU14	23 Nm – 36 Nm	6.8 rad/s – 13.6 rad/s	0.9 kg	74 mm
DT50S-WGA20	39 Nm – 64 Nm	3.4 rad/s – 11.1 rad/s	1.5 kg	94 mm
DT50M-WGU20	73 Nm – 120 Nm	2.3 rad/s – 7.2 rad/s	1.8 kg	94 mm

Note: The table above mentions four out of eight available models for higher torques; please refer to the original reference **[68]**.

Figure 8: MAXON: HPJ – RJ Series. Image reproduced from [68].

Table 12: MAXON: HPJ-RJ series. Reproduced from [68].

HPJ-DT series (Hollow shaft, No brake), System	Peak Joint Torque, Repetitive	Peak Joint Velocity	Mass	Outer Dia	Length
RJ 45	5 Nm – 13 Nm	2.5 rad/s – 7.1 rad/s	1.3 kg	70 mm	104 mm
RJ 60	25 Nm – 65 Nm	3.0 rad/s – 7.2 rad/s	1.8 kg	80 mm	115 mm
RJ 90	39 Nm – 122 Nm	1.7 rad/s – 5.1 rad/s	3.0 kg	110 mm	113 mm
RJ 90 "L"	83 Nm – 260 Nm	1.0 rad/s – 3.2 rad/s	3.4 kg	110 mm	125 mm
RJ 110	175 Nm – 350 Nm	3.4 rad/s – 6.9 rad/s	3.7 kg	110 mm	70 mm

Furthermore, MAXON also offers compact frameless motor kits for high customization and personalized solutions.

2.3.4.2 Erob

The Erob has various models, offering a range of maximum average load toques from 4.8 Nm, eRob70F 14-50, with an outer diameter of 70 mm, length 60.4 mm, and a mass of 0.77 kg [69], to 451 Nm, eRob170H 40-160, with an outer diameter of 170 mm, length 144.9 mm, and a mass of 9.29 kg [21]. These integrated actuators are the lightest and most compacted as far as this research goes. The main issue is the installation or integration into the robot arm system, as the connection parts with the links can introduce considerable weight to it. Figure 9 shows its main components and

Table 13 present five possibly relevant models for the design of wheelchair-mounted assistive robot arms. The connection protocols available are EtherCAT, CANopen, or Modbus.

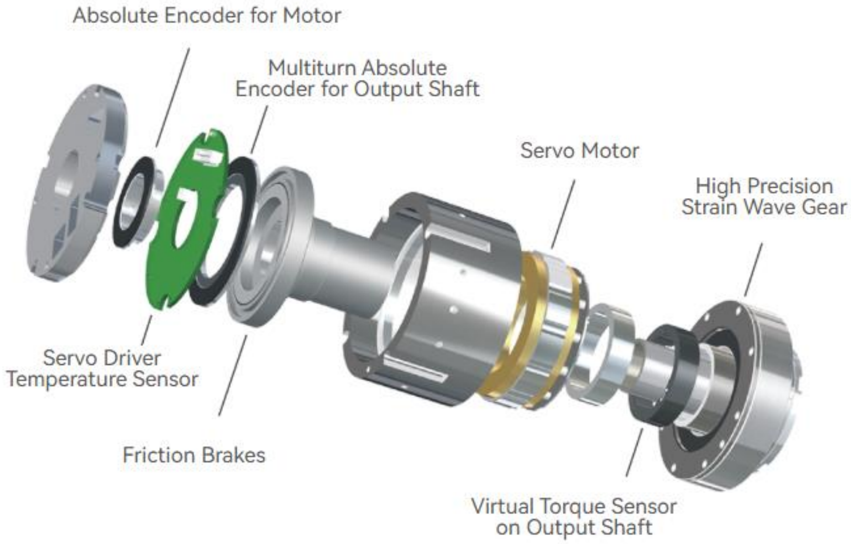


Figure 9: Erob components. Reproduced from [21]

Table 13: Erob: Some relevant models and their characteristics. Reproduced from [57], [21].

Erob	**eRob70F 14-100**	**V5 eRob 70I 14-100**	**eRob80H 17-100**	**eRob90H 20-100**	**eRob110H 25-160**
Peak torque for start and stop (Nm)	19	36	70	107	229
Permissible max. value at average load torque (Nm)	7.7	14	51	64	140
Rated torque (Nm)	5.4	10	31	52	87
Permissible maximum momentary torque (Nm)	35	70	143	191	408
Max. output rotational speed (RPM)	30	30	30	30	18.75

Motor power (W)	75	100	146	300	750
Outer diameter (mm)	70	70	80	90	110
length (mm)	60.4	71	84.2	98.9	115.2
Weight (KG)	0.77	0.88	1.19	1.75	2.88
Power Input Voltage (V)	48				
Hollow diameter (mm)	18				
brake model	friction brake				
Output encoder resolution	19Bit				

2.4 Design Methodologies

To design and develop any project or product, it is crucial to understand and organize the course of action. The established design methodologies provide a guide to do so. This section explores some of the design methodologies that can adjust and contribute to the development of custom-designed integrated robotic actuators for assistive robot manipulators for activities of daily living.

2.4.1 Human-Centered Design (HCD)

Considering the scope of this research is to look forward to developing a product, i.e. a custom-designed integrated robotic actuators, which can be used in the design and development of assistive robot manipulators that interact with humans and their surroundings, the opinions, expectations, and experiences of the customers need to be heavily considered. The Human-Centered design methodology responds to the need to identify the real needs that need to be covered, from the eyes of experts, consumers, designers, users, and stakeholders.

The Human-Centered Design (HCD) methodology as its name suggests focuses on the user's needs, the proper interaction of the machine designed, and the end-user. HCD is also considered a philosophy of design, as it considers the important understanding of human psychology to be applied in the design process as well as its feedback, to ensure that the technology that is going to be developed will be able to communicate with the user and respond appropriately to its capabilities [70]. Also, it highlights the importance of the communication of the machine to signal when something is not working appropriately, allowing the person to notice on time to make the appropriate repairs or take the appropriate actions, this way avoiding fatal damage to anything present in the soundings and the machine [70].

Through observation and communication, HCD looks forward to identifying the real needs and the challenges that the end-user is facing to get to a proposed solution; it uses an iterative process and with constant feedback, that can modify the approach as needed to get to the definition of the problem to solve, the right problem [70]. Due to the use of an iterative process, the invention in the design is relatively incremental rather than a radical one, which may be possible in rare cases [70].

HCD methodology has two major phases and four general steps [70] as shown in **Figure 10**: HCD, Doble diamond general design approach. The first phase considers the finding of the actual problem by observing and generating ideas; in this phase the acquisition of knowledge and context is the key from a divergent perspective of the situation to a convergency of clarity of the problem to solve and its possible initial solution to jump to the second phase [70]. The second phase focuses on the solution, which leads to the exploration, development, prototyping, and testing of the proposed solution, as in the first phase, there is a divergent or opening of ideas in the prototyping of the solution that with the testing if is successful, can lead to a convergence or finding of the real solution [70]. The final product needs to bring a positive experience to the user by being functional, aesthetic, comprehensible, reliable, and safe [70].

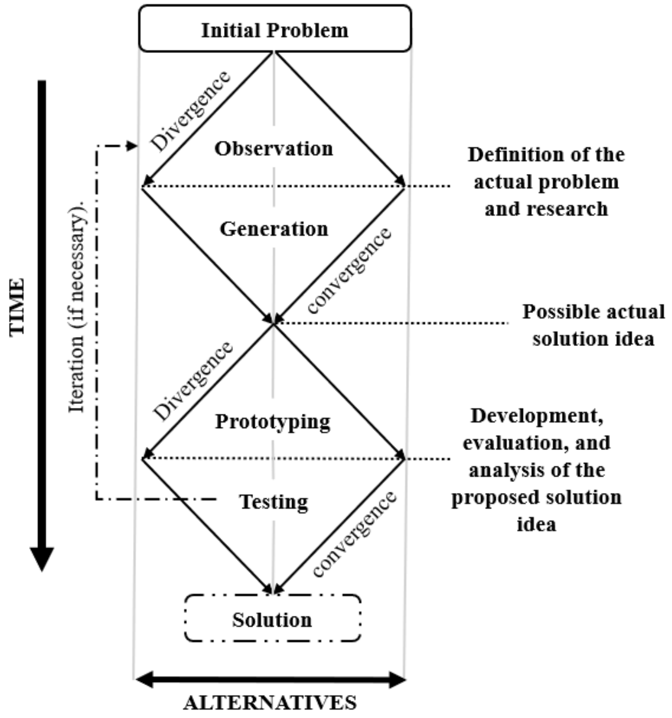
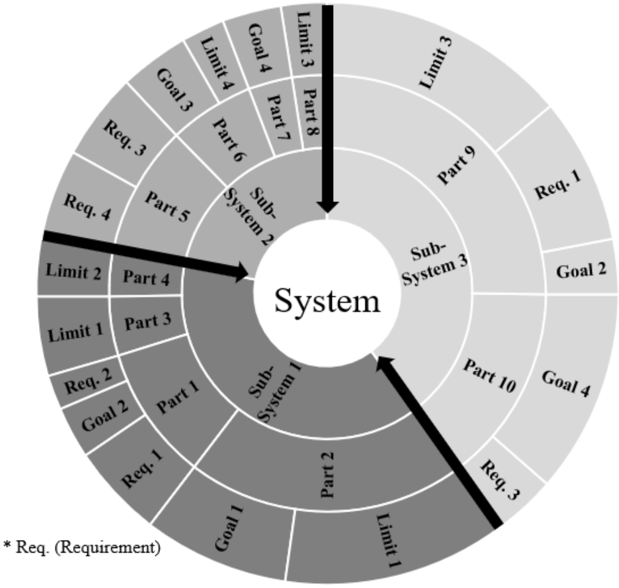


Figure 10: HCD, Doble diamond general design approach.

2.4.2 Systems Design

It is common for mechanical designs to be considered systems or assemblies composed of subsystems or subassemblies composed of parts or components, as shown in **Figure 11**. The design of an integrated costume-designed actuator is not different, the overall design requires detail-oriented analysis of all the interactions of the system to ensure the correct function of components, responding to the design goals and requirements, as well as their performance limitations.

The System Design methodology is used for complex designs, as it considers the global interactions of the design as well as the smallest ones. This methodology divides the global project into subsystems from the most complex part to the simplest, this ensures that every single component is in balance with the rest of them [71]. The analysis of all the components covers their limits and requirements to understand the possible interactions, this considers and classifies the inputs and outputs of the system, the most important input will be the limit for the system but, as all components may have different requirements, a variety of limits will be respected to ensure the harmonic of the system as the correct flow of information ensures its operation [71]. This methodology also considers the use of feedback loops, collecting the data of the performance, evaluating it, and sending a new signal to the system as an appropriate response that can correct any past misbehavior, generating a new one [71]. This methodology is also good for working in teams, as the project responsibilities can be delegated by the different categories of subsystems, ensuring that all components have been taken care of, while all subsystems developed or chosen, must be compatible with the others to compose a balanced system.



* Req. (Requirement)

Figure 11: System Design Diagram.

2.4.3 Agile Development

This methodology is beneficial for product development, as it offers the possibility to test features in different iterations and considers the direct feedback of the end-user to get to the desired performance covering all the initial needs and the new ones that can appear during the different prototype's evaluation. These key aspects are strongly beneficial in the development of integrated actuators as many non-brand-related components could be used to achieve the end goal of the system. Having to answer all the different needs of each component can be complex but the fast-prototyping approach allows the testing of fundamental features in the early stages with a simpler system that will eventually evolve to the final product.

The agile development methodology focuses on fast iterations based on feedback from end-users, this can represent a challenge to apply it, as requires the opinion of qualified customers to work as an active part of the development [72]. This methodology actively considers the participation of the customers, in the first proposal, the initial requirements of the customers will be considered as well as in the development process itself, by being an active part of the team, as the solution that will be presented, is evaluated, and modified based on the feedback received [72]. This is very useful in dynamic environments as the result can adapt to the changing needs quickly. With every iteration, the project gets closer and closer to the final product [73], as it will consider all the needs established and planned at the beginning as well as the new ones that can come out of the testing or user feedback, this process tries to ensure the acceptance of the final version of the project by the end-user [72], the iteration process can be visualized in **Figure 12**: Agile Development iterations diagram. Image reproduced from .

This methodology is mainly used in programming, but its characteristics can be extrapolated to other areas, taking its management perspective. The outcomes of management are the creation, retention, and transfer of knowledge, considering three factors, ability, motivation, and opportunity, been combined with the main characteristics of this methodology that are capable of evocating the perception of usefulness, ease of use, compatibility, and maturity, as well as the capacity to demonstrate it with results [72].

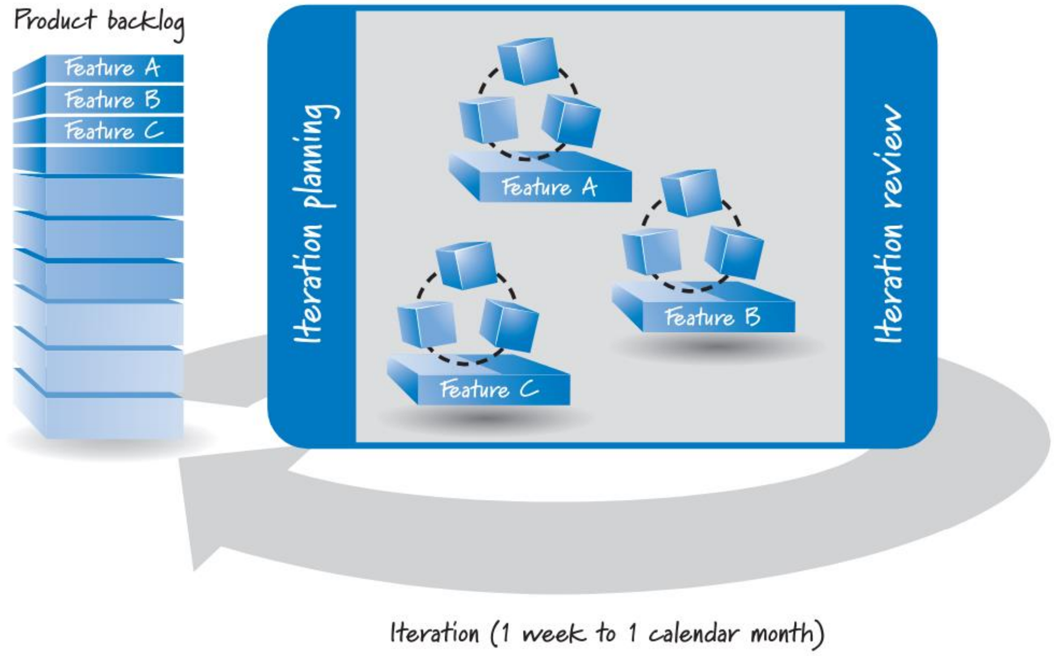


Figure 12: Agile Development iterations diagram. Image reproduced from [73].

2.4.4 Sustainable Design

Sustainability is a critical topic that cannot be left behind in the design process, as every single product will have an impact on people’s lives and, therefore, on the planet. The entire life of a product will impact the environment, from its beginning as an idea being planned up to its end life as disintegrated materials that once were part of a functional product. Since every stage of the process has an environmental impact, it is critical to be aware of it to make an efficient and responsible use of the resources [74]. The waste of resources and carbon footprint can be reduced in multiple ways depending on the stage of the development. Starting with the planning, making a profound search of the state of the art of the topic helps with the gain of understanding of the horizon of the topic, from the positive to adverse impacts, unexplored or undeveloped solutions on specific areas, what is working or not, everything that can help to be better in the making and responsible of the social impact that will generate. Out of the literature review, the knowledge specific to mechanical design contributes to the most appropriate selection of components, materials, production processes, mechanical tolerances, mechanical requirements, mathematical bases for behavior prediction, and more. This knowledge, used properly, can reduce waste as fewer mistakes and remaking will be necessary to achieve the design goals efficiently. Sustainable design is not limited to using environmentally friendly materials or production techniques, socially responsible and energy-efficient designs are desired. It is essential to highlight that responsible mass-produced products are practical, ergonomic, under law or regulated standards, convenient, economical, aesthetic, with pleasant appearance, without excluding the out-of-ordinary, inspiring, art, creative but as technical and complex, and competent solutions [75].

Sustainable design is key to bringing viable financial and socially sustainable solutions, bringing real value to the world under ethical values, this seeks the achievement of all technical requirements of the solution at a reasonable cost, considering all the impacts this has on the planet and humanity, respecting its dignity to not bring more harm to the environment [76]. The development of integrated custom actuators has an environmental impact as well as a social one, being on the core root base for designing assistive robot arms that look forward to helping dignify the lives of people with mobility impairments. The nature of this project requires the use of shipping services to get the necessary components and the manufacturing of custom parts, to help reduce the inevitable carbon footprint, the number of shipments required must be kept to the minimum possible. Also, considering and applying the design principles for economical production will directly influence a more efficient and therefore sustainable design process [77].

2.4.5 Design for Manufacturability (DFM)

The Design for Manufacturability methodology ensures that the design can be manufactured appropriately, the application of the standards and well practices during the design process helps in communication between designers and manufacturers, avoiding requesting impossible parts to manufacture because of the lack of knowledge on the material behavior under the necessary operations. This methodology provides standardized allowed minimal dimensions the part should have, best practice guidelines of mechanical drawings, specific design guidelines for the different production processes, cost-effective design, general advice on design, specific tolerances depending on the manufacturing process, and more [77].

2.4.5.1 Design Principals for Economical Production

The following are some general considerations that can be applied to design for manufacturing at the minimum production cost possible [77]. First, simplify the design as much as possible in terms of shape, number of parts, tolerances, manufacturing time, etc. Second, for materials and components selection, prioritize the use of commercially available materials and components that can be purchased regularly with relatively low waiting time or that are mass-produced to get better prices for the parts to have fewer expenses in keeping inventory. Third, in the case of designing a set of similar products and subassemblies, the use of the same materials and components across the designs can help reduce production costs as larger quantities of the same part can be purchased to be used in different sets. Standardizing parts also helps in quality control. Fourth, avoid the use of tight tolerances; the inappropriate use of these tolerances can highly increase the production cost as much tighter they get, the cost of ensuring them get done increases. The correct use of tolerances helps to ensure the correct functionality of the design. Fifth, in selecting materials, consider its processibility characteristics too, not only the mechanical requirements and upfront cost, since the production time and warranty also affect the overall product’s cost. Sixth, as a designer it is important to collaborate, communicate, or get feedback from manufacturing personnel or engineers to ensure a seamless transition from proposal to reality. Seventh, considering the cost of production, it is beneficial to design for the need of only one primary manufacturing operation, as the simpler, the better; use secondary operations when necessary to ensure the safety, handling, and functionality of the design. Secondary operations like inspections, heat treatments, painting, or any extra postprocessing will generate an extra cost that, depending on the case, can be even higher than the cost of the primary operation. Eighth, to design, you must consider the adequate and most advantageous production process for the specific amount of production that can be expected of the product; this way, the product's sales must be able to cover the production cost of the method selected. Ninth, take advantage of the special characteristics of the manufacturing processes, as some can create specific features, like living hinges or porous surfaces that naturally retain lubricant, without the need for extra operations or even parts. Tenth, be open to advice and decision-making from manufacturing engineers in the production process to choose the most adequate procedures and methods to achieve the dimensions, tolerances, surface finish, and all the requirements specified in the drawings, do not specify the process on the drawings without previous communication.

This methodology considers almost all the key aspects of design, proportioning the theoretical and practical references for production.

2.4.6 Design for Reliability (DfR)

The reliability of a product should be a concern from the beginning; all overall costs related to reliability will decrease for the earliest stage where it is implemented, leaving reliability concerns to the end when the product is "finished" will only increase the expenses in fixing and remaking to counteract undesired performances and even worse if reliability is complexly neglected to be taking care by paying and repaying warranties, as shown in **Figure 13**: Increment of the cost of Unreliability.

Implementation of DfR focuses on having a balance between early investment and long-term costs, the criteria that follow contribute to a faster time to launch products that will generate revenue and have better control of warranty cost as well as a better characterization and performance of the product. DfR looks forward to predicting based on historical data used in the planning and design process, as well as the data obtained from actual tests of the product. The more accurate the prediction, the better informed the decision-making process. Since every decision made will directly contribute to the reliability of the product in a different way, every person involved in the design, production, testing, and selling must be aware of its impact, not only the reliability engineers are responsible for the product performance.

The level of effort put into ensuring reliability should be correlated to the level of impact that a design can have on the safety and well-being of the user and its surroundings. To implement DfR the following should be covered in phases of design:

1. Analysis of the conditions where the product will be used and setting performance goals during a specific interval of time. Develop metrics to
2. In the selection of the main components, it is necessary to distinguish between parts that can be purchased and parts that need to be customized, as the treatment for both is different.
    a. The customized part's reliability is it responsibility of the designer and production team, their experience and professionalism will be reflected in the use of their knowledge to get to the expected performance goals of the product. Reliability will depend on the selection of the appropriate materials, dimensions, tolerances, processes of production, packaging, storage control, and more. The simulations and testing of these parts will help to establish their characteristics, and behaviors in an interval of time under specific conditions, whether it met the reliability goals or not.
    b. Purchased parts come with an already established or known reliability, it is preferable to purchase from companies that take this into account and facilitate the information over the ones that don't. In the case of asking for the information but it is not given by the vendor and this company is the actual only one that has what you need, the only option is to consider the reputation of the company work and test yourself the performance of the parts, keep open communication with the vendors and clear warranty

policies, be aware of the risks and cost that this represents to the designer and the economic impact (and all relevant others) that the failure of this parts can have on the performance.

3. Identify installation requirements and warranties of the components to ensure compliance with them.

Some of the characteristics mentioned are also present in other design methodologies since they directly contribute to the design's final performance.

A better understanding and control of cost throughout the entire life of the product, considering how beneficial it is to implement and be aware of reliability from the beginning, not only do reliability engineers have to work towards it, but designers, manufacturing engineers and sales representatives should ensure the reliability of the product, to identify any failure in the early stages.

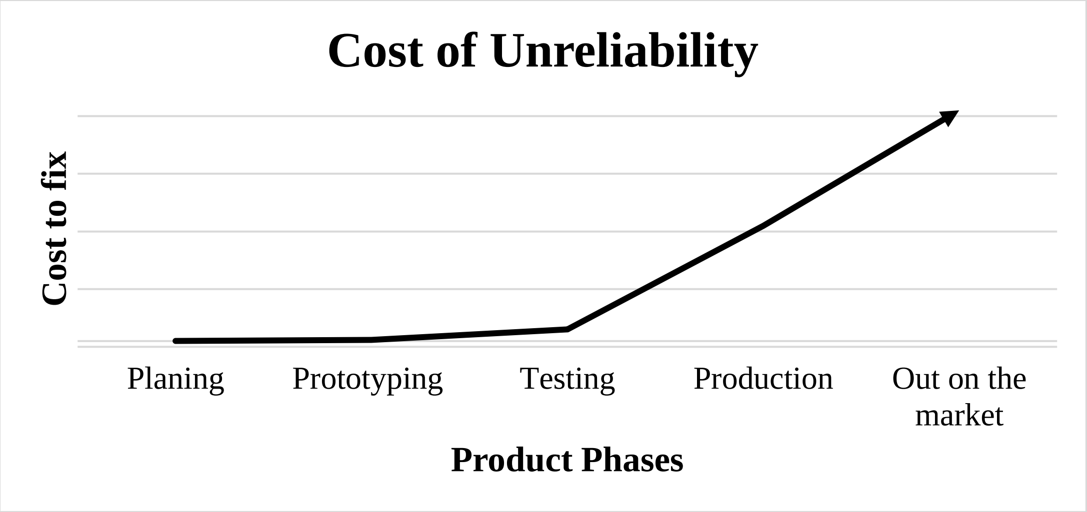


Figure 13: Increment of the cost of Unreliability.

CHAPTER 3

6-DOFs WHEELCHAIR MOUNTED ASSISTIVE ROBOT ARM AT UWM BIO-ROBOTICS LABORATORY

One of the UWM Bio-robotics laboratory areas of research has been wheelchair-mounted assistive robot arms, also known as the mR2A [15]. The mR2A model is one of the many outputs of this research, which has performed well compared to previous documented developments in this field. as seen in Table 3, chapter 2. However, there is room for improvement, especially in the overall weight system, which requires an analysis to identify the points of modification that can improve the payload-to-weight ratio. Multiple aspects can be modified to achieve this weight reduction without affecting performance, keeping the torque capacity of the original model.

3.1 Current state of the robotic arm and weight analysis

The mR2A model is composed of 3D-printed links, integrated actuators, aluminum connecting parts between links and the actuators' housings, aluminum connecting parts between the actuator’s torque output and the following link, an aluminum base for the robot arm for connection with the wheelchair, and an end-effector. Also, electrical connections are internal, passing through the hollow actuators. Furthermore, EtherCAT is the communication protocol used to control the assistive robot arm.

The mR2A model is composed of six QRob actuators; each one uses one mounting aluminum 6061 alloy part due to its structural design, which requires securely fixing the actuator to the link, using the threaded holes present in the harmonic drive circular spline (fixed part), these parts add approximately 1 kg to the system. To reduce this load, the actuator's housing can be redesigned to fix the link appropriately without needing a bulky part. With the addition of two rings around the cylinder housing with threaded holes for the use of M4 x 0.7 screws, depth 4.2 mm. **Table 14** shows the current weight of the actuators per joint and the installation part.

Table 14: mR2A Installed Actuator joints Weight.

Joint	Model	Rate torque (Nm)	Diameter (mm)	Length (mm)	weight (kg)	mR2A Original fixing part mass (kg)	Total weight (kg)
1	QRob80H	31	80	92.3	1.4	0.19	1.59
2	QRob90H	52	90	98.9	2.1	0.17	2.27
3	QRob80H	31	80	92.3	1.4	0.16	1.56
4	QRob70H	10	70	78.3	0.98	0.21	1.19
5	QRob70H	10	70	78.3	0.98	0.14	1.12
6	QRob70F	5.4	70	67.7	0.83	0.13	0.96
				Total	**7.69**	**0.996**	**8.686**

Furthermore, the current overall width of the mR2A robot arm is 148.95 mm (5.86 in), which respects the ADA allowable width of 6 inches for a standard power wheelchair. Moreover, the base connecting the wheelchair with the robot arm has a width of 180.38 mm (7.10 in) and is positioned right next to the wheelchair's seat, from which the max allowable by the ADA is 7.5 inches. Therefore, the width is within the limits. Also, considering bariatric power wheelchairs, the allowed width in the least critical case is 7.38 inches (187.45 mm), making the mR2A compatible. However, in the critical case of the maximums, the width is 2.88 inches (73.15 mm), making it incompatible for this case. Reducing the actuator length can help achieve a slimmer design. This is always desirable, as it can help to gain compatibility with other power wheelchair models and reduce the overall system weight since the link structures can be shorter, have less volume, and therefore reduce the mass. The current total mass of the 3D-printed carbon fiber links is 1.63 kg, and the mass of the connecting parts is 0.97 kg; details can be found on **Table 15**. Considering the results of the dynamic load on ADLs workspaces and the test of 3kg of the mR2A, it is noticeable in all the graphs present that joint 3 takes most of the load in the system, and it reaches its maximum rated torque of 32 Nm at 1.08m from its origin [15]. During the 3kg load testing, the maximum torque register in joint 3 was approximately 37.8 Nm, and in joint 2 it was 31.42 Nm. Therefore, the actuator used in joint 2 could be reconsidered.

Table 15: Links mass considering structure and connecting parts.

Link	Structure Mass (kg)	Shaft to link connecting part, Mass (kg)	Total (kg)
1	0.16	0.15	0.31
2	0.17	0.29	0.47
3	0.36	0.22	0.58
4	0.45	0.20	0.65
5	0.27	0.11	0.38
6	0.21	--	0.21
Total	**1.63**	**0.97**	**2.60**

The actuator assigned to Joint 2, QRob90H, with 52 Nm and 2.1 kg, could be swapped with the QRob80H, with 31 Nm and 1.4 kg. This change can reduce the system's weight by 0.7 kg, and torque requirements can still be met as the QRob80H has a rated torque of 31 Nm and has shown it can supply up to 37.8 Nm.

In summary, the mR2A model performs well but can improve with weight reduction by replacing heavier components, such as the joint two actuators, with lighter alternatives while maintaining torque requirements. Redesigning actuator housing and link dimensions can further enhance the payload-to-weight ratio and compatibility, making the robot arm more efficient and versatile.

CHAPTER 4

DESIGN AND DEVELOPMENT OF CUSTOM ACTUATORS FOR ROBOT JOINTS

4.1 Overview of Methodological Approach to Design

For the design and development of the custom actuator for robotic joints, different methodologies will be combined into one, taking the best of each and the most appropriate approaches that those take to ensure a successful final product. The different methodologies and approaches used are the following: Human-Centered Design (HCD) [70]; Systems Design [71]; Agile Development [72, 73]; Sustainable Design [75, 76]; Design for Manufacturability (DFM) [77] Each methodology has a specific approach to design although there are some similarities, their different focuses together cover the overall aspects of the product, and some will be more heavily used than others in the different phases of the design process.

HCD will ensure that the final product meets the end user's necessities, addressing their challenges and determining the design constraints that translate those challenges into design parameters [70]. These initial design expectations may be unrealistic at the beginning but, combined with other methodologies' focus, these expectations will be evaluated and redefined to get to the final design, which is also influenced by Agile Development and System Design methodologies [71]. Once the general necessities of the end user are addressed, the focus will move to the System Design methodology, as the next step will be the determination of what components will be needed to be implemented in the design to respond to the robot's joint main goal [71]. Having the components identified, this methodology accounts for the determination of their proper interactions with each other and the possible external interactions with the design. This ensures that complex systems like the custom actuator for robotic joints can work together seamlessly. In this stage, more design goals and parameters are established, to move forward, the Agile Development methodology approach is implemented by identifying the simplest possible design to test the correct interaction of the components, an initial iteration that ensures the installation requirements of the components are met, aiming to prove an initial functionality of the design [72, 73]. This methodology allows the final product design to be broken down into simpler iterations that will become more complex and sophisticated as each design evaluation will assess more of the design constraints initially established. In this stage of the process, all the designs from the first iteration to the final product will address multiple focuses by considering three more methodologies simultaneously, as follows: Design for Manufacturability (DFM) [77]; Sustainable Design [75, 76]. This ensures that the design is possible to manufacture and scalable for mass production; the materials selected are durable to avoid environmental waste; the design must ensure easy access for maintenance to the components that required it the most in the system, as well as the use of standard components for the parts they may need a replacement faster than others in the system, like adding grease to the harmonic drive bearings if the sound of the motor has increased with use and time. In-depth, the DFM methodology looks forward to ensuring the manufacturability of all the designs proposed, and the selection of the materials must be appropriate to the application as well as advising to work closely with manufacturing engineers to ensure that the production processes used to achieve the drawing specifications and the appropriated design for the anticipated production scale of the product [77]. At this stage, more design constraints related to the limitations of the material manufacturing techniques are added. This methodology also highlights the benefits of having the least parts possible to accomplish the task. Furthermore, sustainable design will be considered in the materials selection process to ensure mainly durability to avoid constant replacements that may generate environmental waste, recognizing the lifecycle impact on the environment [75]. Also, the Design for Maintainability approach will directly influence the design as it looks after the accessibility to the components that need to be replaced to keep the correct functionality of the overall system. Having to identify the areas of the system that are more critical and ensure access to specific components without the need to disassemble completely saves time in maintenance procedures that are also related to design for reliability as it is more desirable to have a system with a longer time of service than the time it takes to repair, from the cost standpoint a more reliable part will generate more profit and fewer losses during its maintenance time. From the reliability standpoint, although it is more related to the testing of the final product, reliability can be considered in this early stage in a few ways. First, consider what components could fail before others and add redundancy, and a backup system to those. Another option is to identify the potential causes of failure and the way to prevent them as well as add safety measures to ensure the component's safety by adding limits that prevent the system from reaching a dangerous performance. Another option is to request reliability information on the standard components that are being purchased and integrated into the design, knowing that the system will be as weak as the least reliable part of the design and acting on it. Even if a more exact determination of the reliability of the design requires extensive testing, the previous awareness of reliability in the beginning phases of the design will guide it to better performance at the end.

Moving forward from the design proposal phase to the first prototype or iteration, once we have a CAD model of the design or a physical prototype of parts assembled, we can implement again the human-centered design methodology to create spaces to interact with end users and get feedback on the design helps to move forward, evaluating if the design is actually addressing the end user needs, which ones have been met as planned and which ones remain to be addressed as well as to be open to getting new necessities that were not identified at the beginning of the product development. This feedback helps to improve and delimit realistic expectations due to all the constraints that had been added in the way of development, correlating it with the human-centered design and Agile Development methodologies. To finalize the design approach, as we get to a more refined version of the design, in the best-case scenario, a design that addresses all the needs established at the beginning. We can start redesigning the parts again under the DFM, System Design, and Agile Development methodologies, before production starts it is important to evaluate if the design can be modular, if it can keep the concept intact and be resized to accommodate different sizes of the main components, this will lead to also account for new versions of the commercial or standard components, as this analysis may lead to establishing what parts can remain the same for the specific size of the design and which one or which ones will serve as adaptor parts only for a specific part, as it will be seen later in the case of the harmonic drives used in this design.

4.1.1 Steps of the hybrid/mixed design methodology for the design

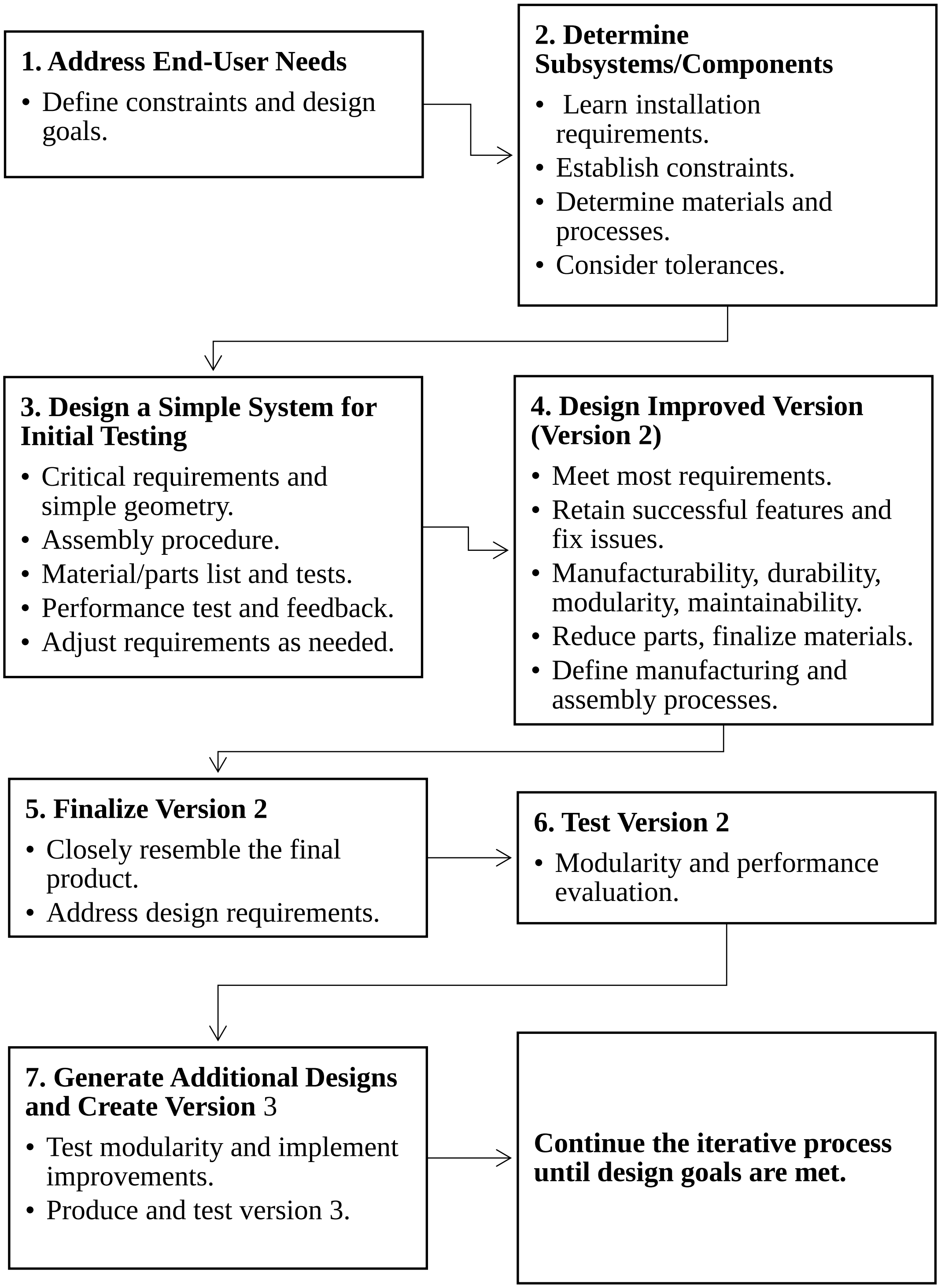
To apply the methodology presented earlier, the detailed design process will follow the steps listed below and a summarized overview is shown in **Figure 14**: A summarized flow diagram of the design methodology was followed

1. Address end-user needs to define the initial design constraints and have a clear statement of the final design goal.
2. Determine the subsystems or components needed to accomplish the goal.
    a. Learn the installation and use requirements of those components.
        i. Establish additional design constraints specific to the installation requirements of each component.
        ii. Determine the materials to be used in this version and the appropriate manufacturing process.
        iii. Consider the material’s tolerances if applicable.
3. Design a simpler system to test the most critical requirements for functionality are being met. This version of the design should be faster to manufacture, and the geometry should be as simple as possible.
    a. Have a clear assembly procedure for version 1 before prototyping.
        i. Optional step: Process like 3d printing on a real scale can help to visualize in more detail how the CAD model will interact with the real world. Other physical representations can help as well independently of the material and process.

    b. Create a list of the materials or parts necessary to complete the assembly and establish the most suitable test to evaluate the performance and functionality of the design.
        i. The tests in the context of this design will look for measuring torque, visual inspection of the correct movements of the motor as commanded, a soft noise indicating no interference of the components, and open visual inspection of the rotor and stator after the design has been used.
    c. Once the performance test is done, take notes of positive and negative points and gather feedback from possible end-users.
    d. Establish more design requirements based on the findings.
4. Design an improved version that will meet most of the requirements, keeping the successful tested features, and fixing any possible issues that could have come up in the testing of version 1. This new version 2 should consider manufacturability, durability, modularity, and maintainability features.
    a. Reduce the number of parts of the system if possible.
    b. Establish the final material for each custom part.
    c. Establish a manufacturing process for the parts and their physical limitations, like minimum thickness.
    d. Establish a clear assembly process for the design before production.
        i. Make sure to identify the tools required to assemble to consider the correct access of those to the places where it will be needed.

5. Version 2 design will be as close as possible to the final product design, addressing most of the design requirements as possible.
6. Perform a test of version 2 and look for improvements.
    a. Analyze the modularity of the design.
    b. Evaluate performance.
7. Generate other designs to prove the modularity of version 2 and generate version 3 with the possible improvements found, produce the design as well as done for version 2 and test.
    a. Identify the parts that can be used as adapters and try to keep the greatest number of standard parts in version 2.

This process of design and interactions can keep going but, we can stop once we accomplish the design requirements. Further improvements still can be made although we will need to continue to prove the functionality of the design one step forward. Showcasing its application to prove its adaptability by design, in this case, a 6 DOFs assistive robot arm, allowing to showcase the different possible placements of the robot joint in a real case scenario; this will be detailed in Chapter 6.



1. Address End-User Needs

- Define constraints and design goals.

2. Determine Subsystems/Components

- Learn installation requirements.
- Establish constraints.
- Determine materials and processes.
- Consider tolerances.

3. Design a Simple System for Initial Testing

- Critical requirements and simple geometry.
- Assembly procedure.
- Material/parts list and tests.
- Performance test and feedback.
- Adjust requirements as needed.

4. Design Improved Version (Version 2)

- Meet most requirements.
- Retain successful features and fix issues.
- Manufacturability, durability, modularity, maintainability.
- Reduce parts, finalize materials.
- Define manufacturing and assembly processes.

5. Finalize Version 2

- Closely resemble the final product.
- Address design requirements.

6. Test Version 2

- Modularity and performance evaluation.

7. Generate Additional Designs and Create Version 3

- Test modularity and implement improvements.
- Produce and test version 3.

Continue the iterative process until design goals are met.

Figure 14: A summarized flow diagram of the design methodology was followed.

4.2 Design and Development of Custom-Designed Integrated Actuators for Assistive Robot Arms

This section aims to explain the process of designing and developing custom robotic actuators for assistive robot arms. The goal is to create compact, modular actuators with hollow structures supporting easy cable routing and installation. This section describes the components selected for the actuator, their design constraints, and how they are integrated into the final product. By following the design methodology steps, the proposed actuator aims to meet performance requirements while being reliable and simple to manufacture.

4.2.1 Design Goals and Requirements of the Integrated Actuators to Response to the Needs of Assistive Robot Arms

The present project looks forward to developing a custom robotic actuator for a robot joint, considering a modular installation, as compact design as possible, and a hollow frame for more accessible cable connections. Due to the hollow design requirement, all the components used need to be hollow or allow their connections to the system to not interfere with the path for cable connection. Also, the commercial components must be reliable, simple to control, and integrated by the end-user. Furthermore, the main application of this design is to be integrated into robot arms, more specifically, to achieve better results than those obtained with the mR2A design.

Based on Mr2A, strengths, and points of improvement, the following considerations and requirements are set:

- The hollow actuator diameter must respond to the electrical connection needs of the EtherCAT Communication protocol. Also, the electrical connections of the integrated actuator driver or controller must be met. The sizing of the connectors and cables will set the dimensions once the motor and driver selection are done.

- The system's voltage will depend on the future selected motor's driver.
- Outside diameters of integrated actuators must not be the greater than the actuators used in the mR2A model to ensure improvement. Therefore, it must be less or equal to 90 mm.
- The height or length of the actuator joint must be less than 92.3 mm for actuators with a close torque to 31 Nm and 78.3 mm for actuators with torque close to 10 Nm.
- The actuator's torque ranges must at least achieve the maximum registered on the 3 kg load test, approximately 37.8 Nm, as well as the minimum to provide the selected rate torques of 10 Nm, 31 Nm, not considering the 52 Nm rate torque as it far away from the maximum demanded for joint 2, 31.42 Nm.

4.2.2 Design Components Selection and Component's Constraints

To accomplish the set design goals, the custom-designed integrated robotic actuators are composed of an EC frameless motor, Harmonic Drive, holding brake, bearings, and custom parts like a housing frame, a shaft, a cover, and an adaptor part. Also, a separate but attachable unit of the motor controller. The following describes each component at its constraints.

1. **Motor:** The selected base motor is a hollow frameless EC Maxon motor, brushless DC, composed of just the rotor and the stator with its electronic circuit, that offers a variety of versions with different torque capacities keeping their hardware dimensions for different voltages, and currents. Also, the same model can be found in different sizes that give more torque options. These models offer more flexibility to customize and adapt to the needs of the application, giving more control to the designs over the final length of the assembly to the

system and the number of parts required. Maxon, as a brand, offers high standards in quality, performance, and reliability [78]. The data sheets they facilitated are complete with important information as well as their installation manuals [79].

The models selected are the EC Frameless 60 flat Maxon Motor (EC60) and the EC Frameless 45 flat Maxon Motor (EC45), both in 48V versions. The EC60 motor will be used in the first and main version design, and the EC 45 motor will serve as a base to prove the modularity to scale down the integrated actuator. Furthermore, the datasheet can be found in **Appendix A** for EC 60 and **Appendix B** for EC 45.

Figure 15: EC Frameless flat Maxon motor, rotor and stator. Image reproduced from [79].

Considering that robot arms depending on their design have different torque needs in their joints, it is better to have a range of actuators that can be positioned as needed, therefore the motor as the starting point as a middle ground is the EC60 with an expected torque range considering the efficiency of 0.281 Nm (Nominal) up to 4.408 Nm (Stall). For lower torque needs the EC45 with a torque range considering efficiency of 0.113 Nm (Nominal) up to 0.771 Nm (Stall). More details can be found in **Table 16**: Some Key Values of the EC60 and EC45 Maxon Motors, reproduced from their data sheet, are present in Appendix A and Appendix B .

Table 16: Some Key Values of the EC60 and EC45 Maxon Motors, reproduced from their data sheet, are present in Appendix A [80] and Appendix B [81].

Model	**EC60-550154-100W-48V**	**EC45-574037-70W-48V**
Weight (kg)	0.333	0.143
Diameter (cm)	60	43.4
Length (cm)	37	28.7
Nominal Current (A) (max. continuous current)	2.78	0.936
Nominal Torque (mNm) (Max. cont. Torque)	319	134
Max. efficiency	88%	84.30%
Nominal T * Efficiency (Nm)	**0.280720**	**0.112962**
Stall Current (A)	43.80	6.97
Stall Torque (mNm)	5010	915
Stall Torque (Nm)	5.010	0.915
Stall T * Efficiency (Nm)	4.4088	0.7713
No load speed (rpm)	3970	3440
No load current (A)	0.1870	0.0481
Nominal Speed (rpm)	**3490**	**2540**
Rotor inertia (gcm^2)	1246	240

A Brushless DC motor's service life is limited by the bearing's life which is better predicted and understood than the life of brushes. Having a longer service life, and higher speed with fewer vibrations, but generates higher torque by increasing the number of magnetic poles which considerably reduces the speed. For this application, the higher torque capacity is more important than the speed, for safety reasons, the maximum speed of the end-effector tool movement advised around humans is 250mm/s by International standards ISO 10218–1:2011 [82].

2. **Motor's Controller:** Considering the importance of the compatibility of control over the motors selected from their electronic notes shown in **Appendix A** , the EPOS4 Disk 60/8 EtherCAT, shown in **Figure 16**: EPOS4 Disk 60/8 EtherCAT, is an EtherCAT digital positioning controller with continuous operational current of 8 A and voltage of 12 - 60 VDC, that works for DC and EC motors. For Physical characteristics, this compact design has a hollow center diameter of 14 mm, an external diameter of 60mm, and a height of 22 mm. With an approximated weight of 26 g and four mounting holes for M2 screws [83]. Although the company offers CAN and EtherCAT communication, EtherCAT offers more robust characteristics appropriate for this application in terms of security, speed, and bandwidth [84]. All the technical data is presented in **Appendix H** .

Figure 16: EPOS4 Disk 60/8 EtherCAT, reproduced from [83].

3. **Harmonic Drive:** The transmission system selected is a harmonic drive, ultra-slim, that will increase the output torque and reduce the incoming speed of the motor to a slower output of the integrated actuator, as shown in **Figure 17** and **Figure 18**. For the EC60 frameless motor, the harmonic drive versions SHD-17-100 and GHD-17-100 are selected, both are dimensionally similar except for the connection point of the output torque this decision looks forward to proving the possible modularity on the design proposal, in case one of the models

gets discontinued. In terms of output torque considering the rated torque at 2000 rpm the difference is 0.3 Nm, and the stall torque difference is 1 Nm, in both cases the SHD 17 has a little bit more capacity. In the same way, for the EC 45 motor, the selected harmonic drives are the versions SHD 14-100 and GHD 14, in terms of output torque considering the rated torque at 2000 rpm the difference is 0.1 Nm and the stall torque difference is 2 Nm, in both cases the SHD 14-100 has a little bit more capacity. More technical data can be found in

4.

5. **Table** 17: Harmonic Drive data models SHD and

6. **Table** 18: Harmonic Drive data models GHD , as well as in **Appendix C** .

Table 17: Harmonic Drive data models SHD

Model	**SHD-17-100**	**SHD-14-100**
Diameter (mm)	80	70
Hollow D (mm)	15	11
Length (mm)	18.5	17.5
Theoretical Weight (kg)	0.42	0.33
Rated Output Torque (Nm)	**16**	**5.4**
Rated Input Speed (rpm)	2000	200
Limit for average input speed (rpm) (with Grease Lubricant)	3500	3500
Limit for Average torque (Nm)	27	7.7
Limit for Repeated Peak Torque (Nm)	37	19
Limit for Momentary Peak Torque or Stall Torque (Nm)	**71**	**35**
Starting Torque (Nm) (Input)	0.17	0.048
Allowable Moment load Mc (Nm)	62	37
Max. Input Speed (rpm)	7300	8500
Ratio	100	100

Note: The maximum moment load must be less or equal to the allowable moment Mc.

Table 18: Harmonic Drive data models GHD

Model	GHD-17-100	GHD-14-100
Diameter (mm)	80	70
Hollow D (mm)	15	11
Length (mm)	18.5	17.5
Rated Output Torque (Nm)	**15.7**	**5.3**
Rated Input Speed (rpm)	2000	3000
Start Stop Allowable Max Torque (Nm)	41	18
Allowable Maximum value of Average Load Torque (Nm)	22.5	7.5
Allowable Instant Maximum Torque (Nm)	**70**	**33**
Max. Input Speed (rpm)	8000	8000
Ratio	100	100

Furthermore, the harmonic drives are compatible with the motors previously selected as the torque capacity of the motors is bigger than the starting torque required. These harmonic drives will set the output speed and torque of the integrated actuator.

Figure 17: 3F FAMED, SHD series Harmonic Drive, reproduced from [85].

The SHD series of harmonic drives are an “ultra-flat shape with a hollow structure; equipped with high rigid cross roller bearing; quiet operation and small varication; high precision accuracy; coaxial input and output, simple and compact structure; zero backlashes” [85].

Figure 18: GIGAGER Precision Technology Co., Ltd, GHD series Harmonic Drive, reproduced from [86].

7. **Holding Brake:** As a safety feature, the addition of a holding brake to keep the position of the actuator in place once the power is off, helps in the design of robot arms to maintain folding status, hold a load in the case of a power off or an emergency stop without relying directly on the motor. Considering the requirements of saving space, the selected brake is an overexcitation-holding brake ultra-slim design, As shown in **Figure 19**, that does not significantly change in length for the variety of toque capacities offered by the MBS series of Chain Tail Co., Ltd. Company, other actual hollow options present more variability in length. Also, they give the freedom to customize a hub to save even more space or use their provided hub, although this brake is not advertised as hollow, the inner diameter of the hub provided is larger than the 11.68 mm RJ45 connector head of an EtherCAT cable. Since two different

motors are been considered, the selected brake for the EC 60 motor is MBSS13AA, and for the EC 45 motor is MBSS05AA [87]. Some of the most relevant technical data can be seen in **Table 19**: Technical data of MBSS13AA and MBSS05AA, and **Appendix G**

Table 19: Technical data of MBSS13AA and MBSS05AA

Model	**MBSS13AA**	**MBSS05AA**
Hollow Hub Inner Diameter: d (mm)	14	14
Hollow Magnetic Yoke Inner Diameter: B (mm)	15	15
Hollow Magnetic Yoke External Diameter: A (mm)	56	48
Height without Hub: D (mm)	14.5	14
Height with Provided Hub: I (mm)	18.7	18.2
Weight (Kg)	0.158	0.108
Torque or Static Friction (Nm)	**1.32**	**0.62**
Overexcitation controller (V)	24	24
Holding (DC) (V)	12	12
Allowable speed (rpm)	**5000**	**5000**
Moment of Inertia (g*cm^2)	2.70E-07	1.10E-07

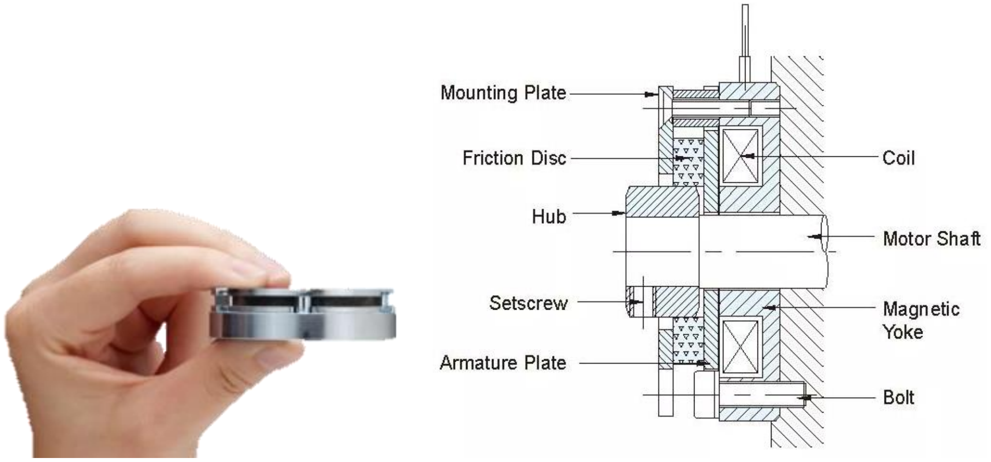


Figure 19: Overexcitation Holding Brake-Ultra Slim, MBS Series by Chain Tail Co., Ltd, reproduced from [87].

8. **Bearings:** To ensure alignment of the shaft the installation of ball bearings to connect static and dynamic components is required. In this case, one of the critical points is the fixing of the brake to the housing structure and its mobile connection to the shaft. The commercial and standard bearings available will dictate at some point the required external diameter of the custom shaft to ensure the fit. The variety selected is Deep groove ball bearings - Single-row - Shielded/sealed type – Contact sealed [88]. These types of bearings handle radial and axial loads at high-speed operations while reducing noise and vibration [89]. One of the bearings selected is the reference 6703 2RS, technical data can be found in **Appendix I** .

Figure 20: Ball Bearing, 6703, 17X23X4, reproduced from [90].

4.2.3 Mechanical Design and CAD Model

4.2.3.1 Materials Selection and Design Considerations Taken

The majority of custom metallic parts are made of Aluminum 6061 alloy, bringing the stability necessary and the machinability, also the criteria to design for aluminum machining is well known and is soft enough to be mechanically processed comfortably. The second material used is nylon, specifically for custom seals, as it offers a high-temperature resistance and does not carry any significant load. The third material used is Stainless Steel 304 alloy for the shaft in versions 2 and 3 of the design.

4.2.3.2 CAD Design

To design the integrated actuator, all the components were digitally represented by 3d models, either provided by the sellers or recreated as needed, all models provided were evaluated to ensure a real representation of the physical components, and the necessary adjustments were made. To start with the design, the layout of connections was decided as follows:

4.2.3.2.1 Version 1

Implementation of EC 60 motor and SHD-17-100 harmonic drive, with custom simple housing, shaft, and cover. Version 1 aims to verify the correct installation of the motor and to explore the possible connection from the shaft to the harmonic drive. The air gap between the rotor and stator (1.1 mm) as well as its concentricity is critical for the performance. Failing to maintain the air gap distance can damage the stator and the rotor due to collision. To maintain concentricity and separate dynamic parts from static ones, ball bearings are added and arranged with a fixed base to keep the harmonic drive’s lubricant grease away from the motor. See **Figure 21** for more details, note that the design has already considered the hollow feature to facilitate cable connections to pass through, and the harmonic drive inner diameter is the one limiting the canal size. Also, in this version, there are seven custom parts.

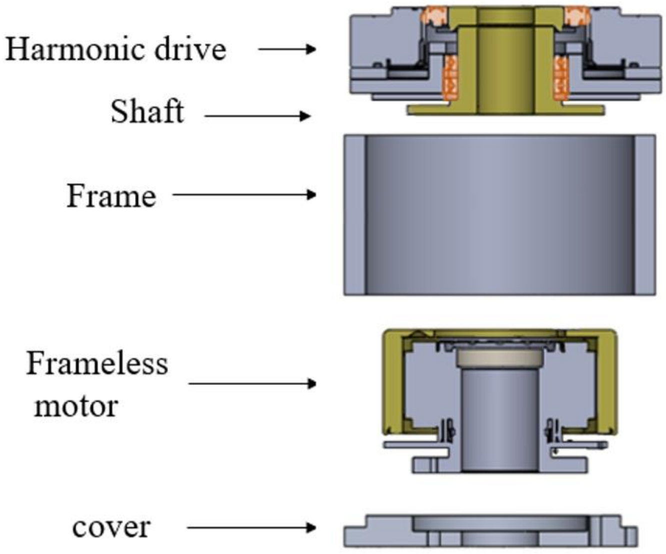


Figure 21: Version 1 layout. Also, moving parts are in yellow, bearings in orange, and fixed parts in grey color.

4.2.3.2.2 Version 2

Developed after the testing of Version 1, Version 2 keeps the successful dimensions and gets updated to a more complex design that gets closer to the design requirements. This version makes the addition of a brake, the model MBSS13AA to the EC 60 motor, and the SHD-17-100 harmonic drive, with detailed housing, as shown in **Figure 22**, features for the installation of the integrated actuator. Version 2 aims to verify the correct installation of the brake, requiring many dimensional adjustments and redesign of the custom parts. The back cover also accommodates the installation of the motor's driver as an option. See **Figure 23** for more details, note that the threaded holes surrounding the housing offer multiple options to choose from as fixing points to an external structure. Also, they are not through holes, therefore the possible screws installed will not pass through, preventing them from damaging the rotor structure.

Figure 22: Version 2, external view.

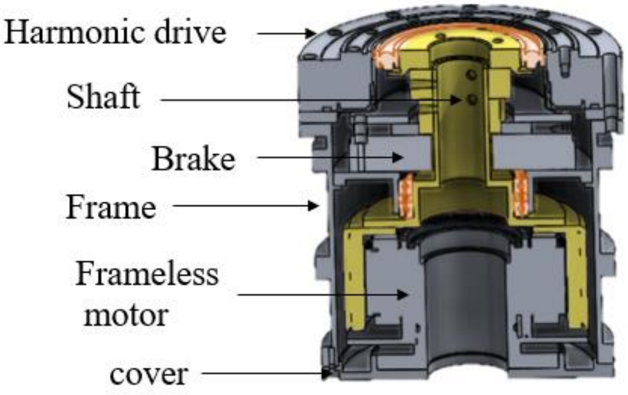


Figure 23: Version 2 layout. Also, moving parts are in yellow, bearings in orange, and fixed parts in grey color.

4.2.3.2.3 Version 3

Developed after the testing of Version 2, Version 3 keeps the successful dimensions and adds two more parts, even though the previous design had no issues, a seal and a ball bearing are added with no need for any dimensional changes. This version is considered the final product as of the extent of the present document and is further recalled as Model 1, shown in **Figure 24**. Moving forward, to prove the modularity of the design proposed, Model 2 is developed by changing the harmonic drive from SHD 17 to GHD 17 needing to custom only one part, the connection between the shaft and the new harmonic drive, as shown in **Figure 25**. Going even further, the proposed layout for Model 1 is scaled down to meet the requirements of the EC 45 motor, SHD 14-100 harmonic drive, and the MBSS05AA brake, bringing to life Model 3, shown in **Figure 26** and **Figure 27**. As in Model 2, Model 4 is designed by changing the harmonic drive to GHD 14 and customizing the connection part from the shaft to the harmonic drive.

On the other hand, improvement of Version 2 and proof of modularity with the presentation of 4 final models. Two models are based on the EC 60 motor and two more are based on the EC 45 motor. Scaling down the configuration done for the original version of EC60 to the requirements of the EC45.

Model 1: EC 60 + SHD 17 + MBSS13AA + Seal.

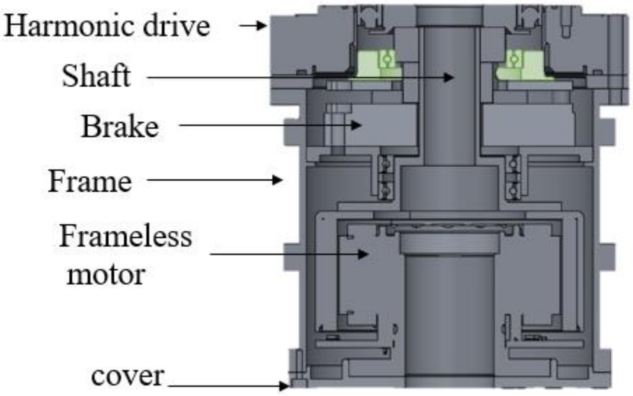


Figure 24: Model1, EC 60 + SHD 17 + MBSS13AA + Seal.

Model 2: EC 60 + GHD 17 + MBSS13AA + Seal

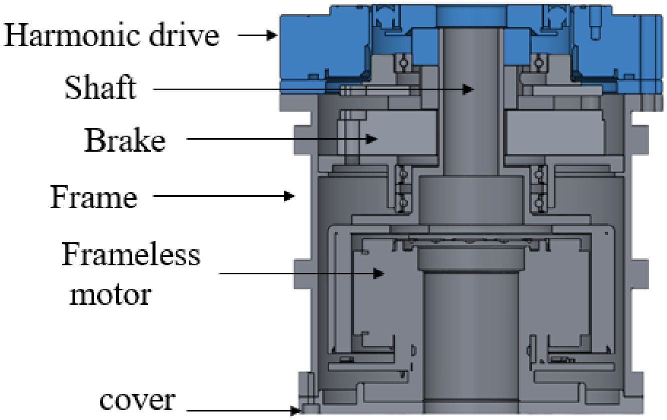


Figure 25: Model 2, EC 60 + GHD 17 + MBSS13AA + Seal.

Model 3: EC 45 + SHD 14-100 + MBSS05AA + seal.

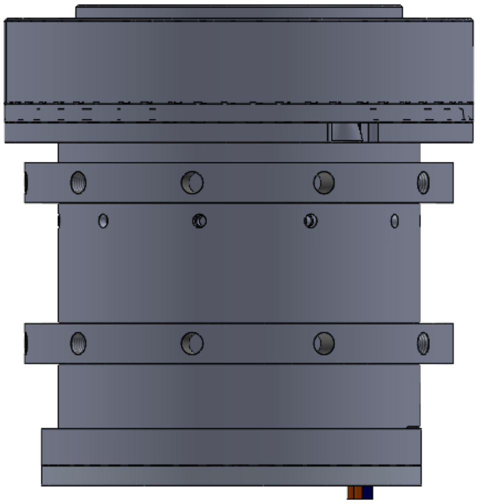


Figure 26: Model 3, external view.

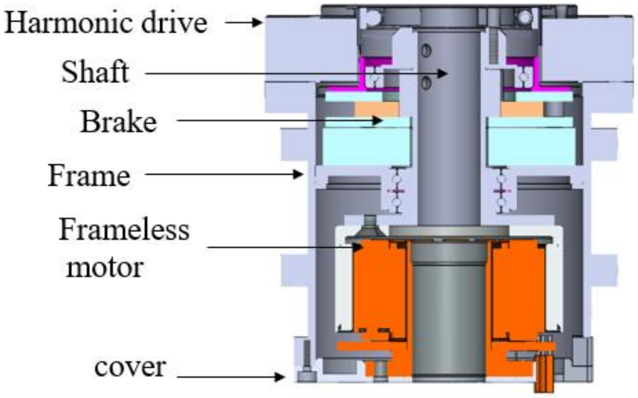


Figure 27: Model 3, EC 45 + SHD 14-100 + MBSS05AA + seal.

Model 4: EC 45 + GHD 14 + MBSS05AA + seal.

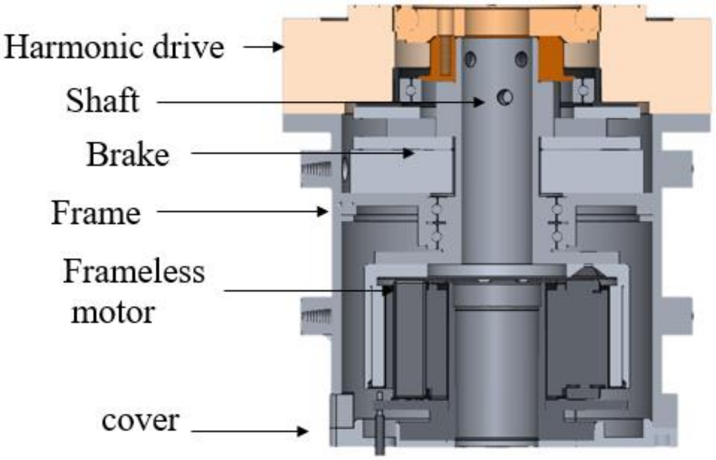


Figure 28: Model 4, EC 45 + GHD 14 + MBSS05AA + seal.

4.2.4 Stress and Fatigue Testing

Considering Model 1, version 3, its housing is evaluated for a torque of 50 Nm, a more significant torque than the motor's theoretical nominal torque of 31.9 Nm. Figure 29, shows the toque's vector placement in purple and the fixing points in green. Furthermore, the simulation is based on the values in Table 20, presenting the properties of the part, material, and simulation mesh.

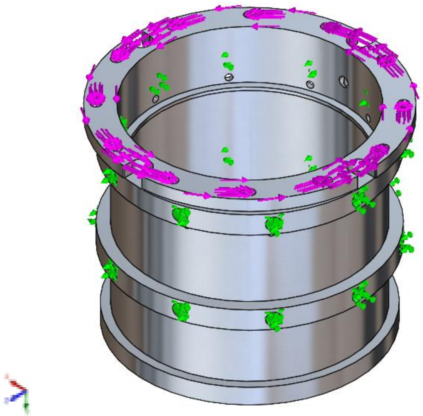


Figure 29: Model 1: Version 3, Torque placement, and fixing points.

Table 20: Properties of the material and Simulation Mesh.

Volumetric Properties	Material Properties	Test Mesh Information
Mass: 0.0953934 kg **Volume:** 3.53309e-05 m^3 **Density:** 2,700 kg/m^3 **Weight:** 0.934855 N	**Name:** 6061-T6 (SS) **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 2.75e+08 N/m^2 **Tensile strength:** 3.1e+08 N/m^2 **Elastic modulus:** 6.9e+10 N/m^2 **Poisson's ratio:** 0.33 **Mass density:** 2,700 kg/m^3 **Shear modulus:** 2.6e+10 N/m^2 **Thermal expansion coefficient:** 2.4e-05 /Kelvin	**Mesh type:** Solid Mesh **Mesher Used:** Blended curvature-based mesh **Jacobian points for High-quality mesh**: 16 Points **Maximum element size:** 7.67003 mm **Minimum element size:** 0.765367 mm **Mesh Quality:** High

The studies simulated are the following: Von Mises Stress, displacement, strain, and factor of safety. Results are presented in **Table 21**. From where, it can be concluded that part can be used as intended without damage. The Maximum von Mises stress is 11.58 MPa, less than the minimum present in the S-N curve for Aluminum 6061-T6, 82 MPa at 108 cycles. Refer to **Appendix L** for all the simulation plots and **Appendix M** for the graph of the S-N curve.

Table 21: Results: Mesh Details, resultant forces, and studies results.

Mesh information - Details	**Resultant Forces**	**Study Results**
Total Nodes: 43579 **Total Elements:** 22971 **Maximum Aspect Ratio:** 53.175 **% of elements with Aspect Ratio < 3:** 81.2 **Percentage of elements with Aspect Ratio > 10:** 0.805 **Percentage of distorted elements**: 0 **Time to complete mesh (hh;mm;ss):** 00:00:11	**Reaction forces:** **Selection set:** Entire Model **Units:** N **Sum X:** 0.0102251 **Sum Y:** -0.00254336 **Sum Z:** 0.011024 **Resultant:** 0.0152496 **Free body forces:** **Selection set:** Entire Model **Units:** N **Sum X:** 0.00318732 **Sum Y:** -0.00204679 **Sum Z:** 0.00478356 **Resultant:** 0.0152496 **Reaction moments:** **Resultant:** 0 Nm **Free Body Moments:** **Resultant:** 1e-33	**Stress:** **Type:** Von Mises Stress **Min:** 28.906N/m^2 **Node:** 23485 **Max:** 11,582,757.000N/m^2 **Node:** 36647 **Displacement:** **Type:** URES: Resultant Displacement **Min:** 0.00000mm **Node:** 1 **Max:**0.00213mm **Node:** 228 **Strain:** **Type:** ESTRN: Equivalent Strain **Min:** 3.900e-10 **Element:** 17060 **Max:**1.455e-04 **Element:** 13803 **The Factor of Safety:** **Criterion:** Max von Mises Stress **Min:** 23.74 **Node:** 36647 **Max:** 9513635.00 **Node:** 23485 **The factor of Safety distribution: Min FOS:** 24

4.2.5 Manufacturing Process and Prototyping

Considering the application of the design and the materials selected, the primary manufacturing process applied is metal CNC machining; version 1 was purposely designed as simple as possible; this design is bulky as the focus was to produce as fast as possible. Ensuring that all the parts have at least one flat face. And keeping only the most critical features for the correct placement of the components. As shown in **Figure 30**.

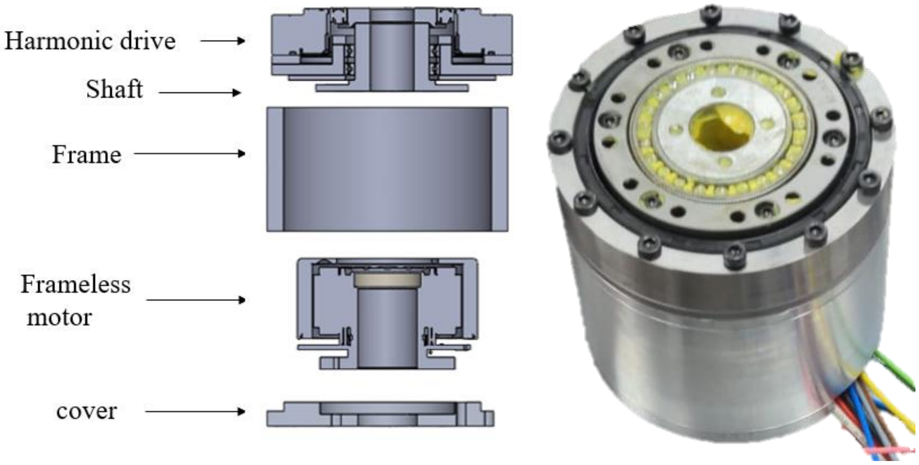


Figure 30: Version 1 Prototype.

Furthermore, considering the complexity of Version 2, an initial 3d printed version of the parts was made, giving a physical reference. Once no issues were found, the prototype of Version 2 was produced by applying metal CNC machining. Furthermore, the seal added inside Version 2 was

3d printed in nylon filament. Making it the definitive design version, version 3, Model 1. As shown in **Figure 31**.

Figure 31: Final product, Version 3, Model 1.

CHAPTER 5

TESTING EXPERIMENTS, RESULTS AND DISCUSSIONS

To validate and characterize the new integrated actuators being developed, a general run test must be conducted, followed by stall torque testing and a comparison with the theoretical values calculated before building them.

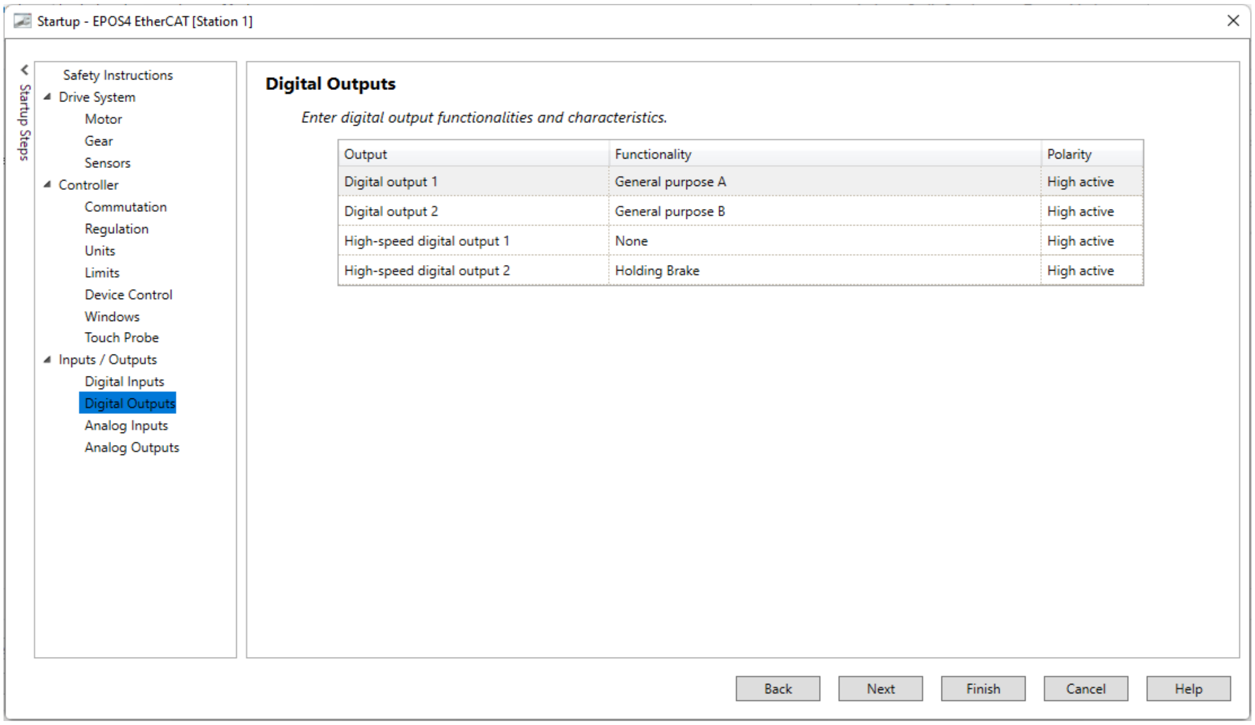
5.1 Evaluation of the Designs

The evaluation of the actuators begins with the assembly process; all the custom parts are measured, and the fits between parts are revised. Once the assembly is completed, it is weighted. As shown in **Figure 32**, Version 1 weighs 2.403 lb or 1.089 kg, and the final version weighs 2.460 lb or 1.115 kg.

Figure 32: Actuators weight, initial and final version.

Furthermore, to evaluate the design, the electrical connection and control of the integrated actuator are set as follows:

- Connect the integrated actuator to the previously selected EPOS4 Maxon Positioning Controller Data. Connect the EC 60 motor and the brake, as necessary, to the controller.
- Connect the EtherCAT cable connecting the EPOS4 Disk 60/8 EtherCAT to the computer with the software EPOS Studio 3.7 installed.
- The Controller is connected to the power supply at 48V and 5 A.
- Run the software, provide the requested data for all the components, and start the actuator's tuning. See **Appendix J** with the complete information. Note that the software will recognize if a brake is connected to the controller and automatically activate its control. As shown in **Figure 33**, this is the only difference between the initial and final versions of the software setup.
- Once the actuator is set in the software, the process for tuning starts, as shown in **Figure 34**, **Figure 35**: Velocity tuning, initial version. and **Figure 36**: Position Tuning, first version., tuning of the initial version. Also, **Figure 37**: Current Tuning, final version., **Figure 38**: Velocity Tuning, final version, and **Figure 39**: Position Tuning, final version. The process of tuning will calculate the best parameters for controlling the system.

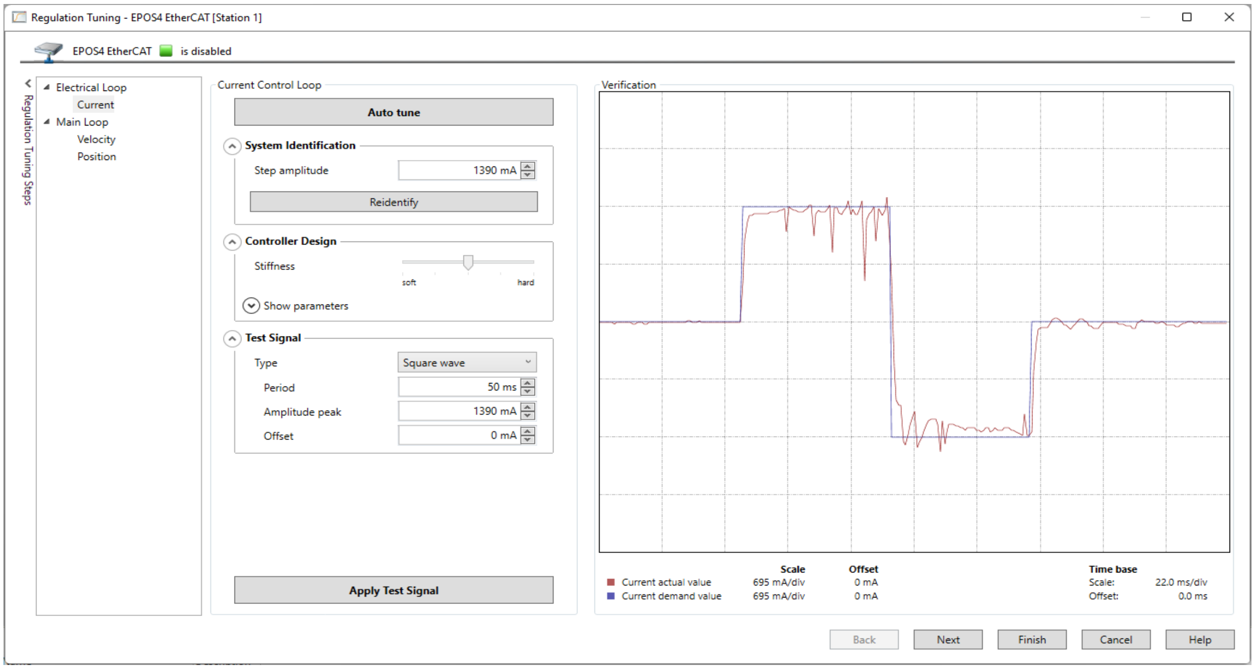


Digital Outputs

Enter digital output functionalities and characteristics.

Output	Functionality	Polarity
Digital output 1	General purpose A	High active
Digital output 2	General purpose B	High active
High-speed digital output 1	None	High active
High-speed digital output 2	Holding Brake	High active

Figure 33: Digital Output, Holding Brake Recognition.



EPOS4 EtherCAT 🟩 is disabled

System Identification

Step amplitude: 1390 mA

Controller Design

Stiffness

Test Signal

Type: Square wave

Period: 50 ms

Amplitude peak: 1390 mA

Offset: 0 mA

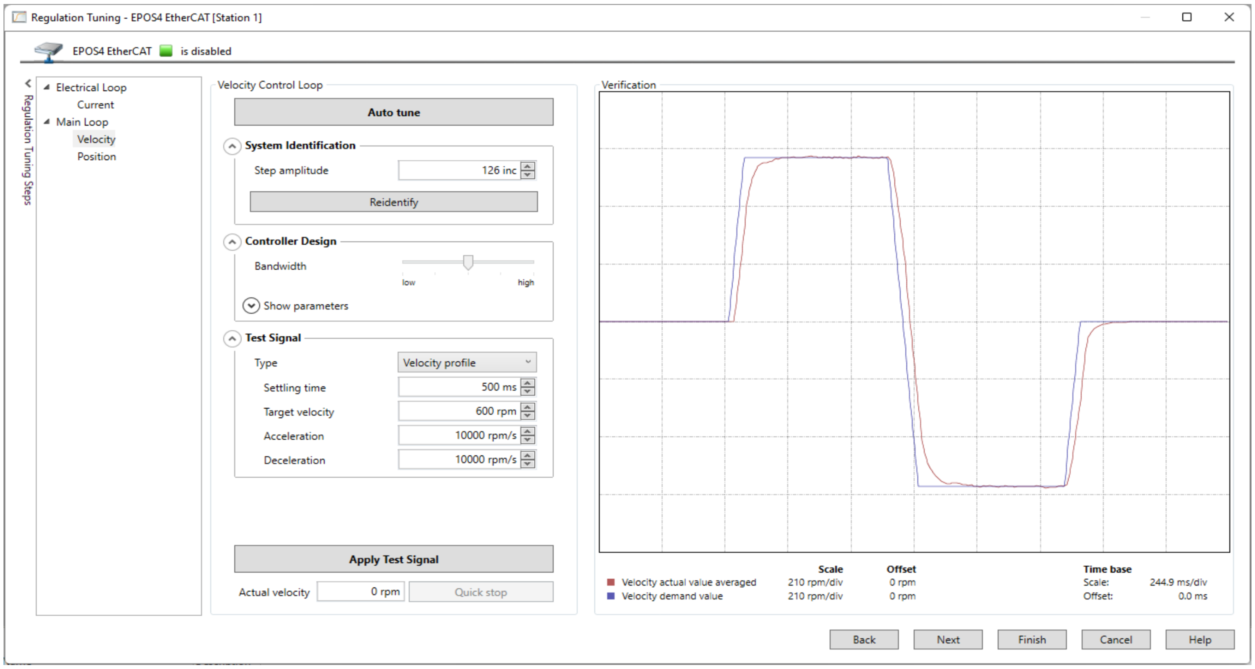
	Scale	Offset
🟥 Current actual value	695 mA/div	0 mA
🟦 Current demand value	695 mA/div	0 mA

Time base

Scale: 22.0 ms/div

Offset: 0.0 ms

Figure 34: Current Tuning, Initial version.



Step amplitude: 126 inc

Type: Velocity profile

Settling time: 500 ms

Target velocity: 600 rpm

Acceleration: 10000 rpm/s

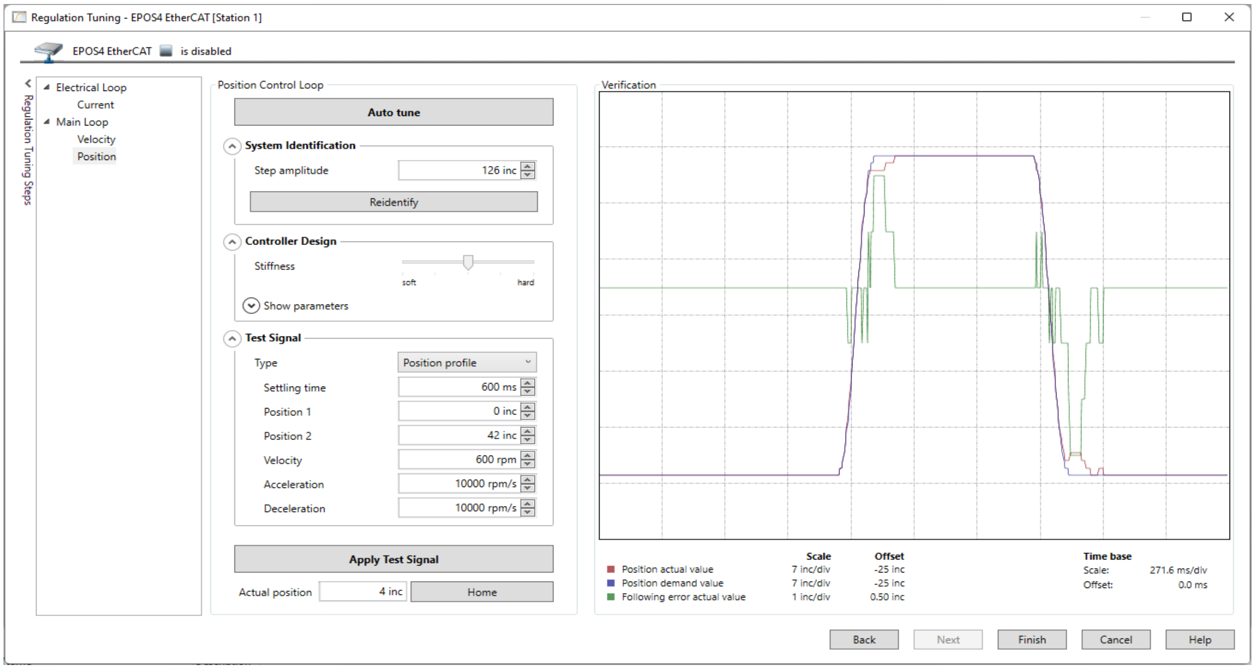
Deceleration: 10000 rpm/s

Actual velocity: 0 rpm

	Scale	Offset
🟥 Velocity actual value averaged	210 rpm/div	0 rpm
🟦 Velocity demand value	210 rpm/div	0 rpm

Time base
Scale: 244.9 ms/div
Offset: 0.0 ms

Figure 35: Velocity tuning, initial version.



Step amplitude: 126 inc

Type: Position profile

Settling time: 600 ms

Position 1: 0 inc

Position 2: 42 inc

Velocity: 600 rpm

Acceleration: 10000 rpm/s

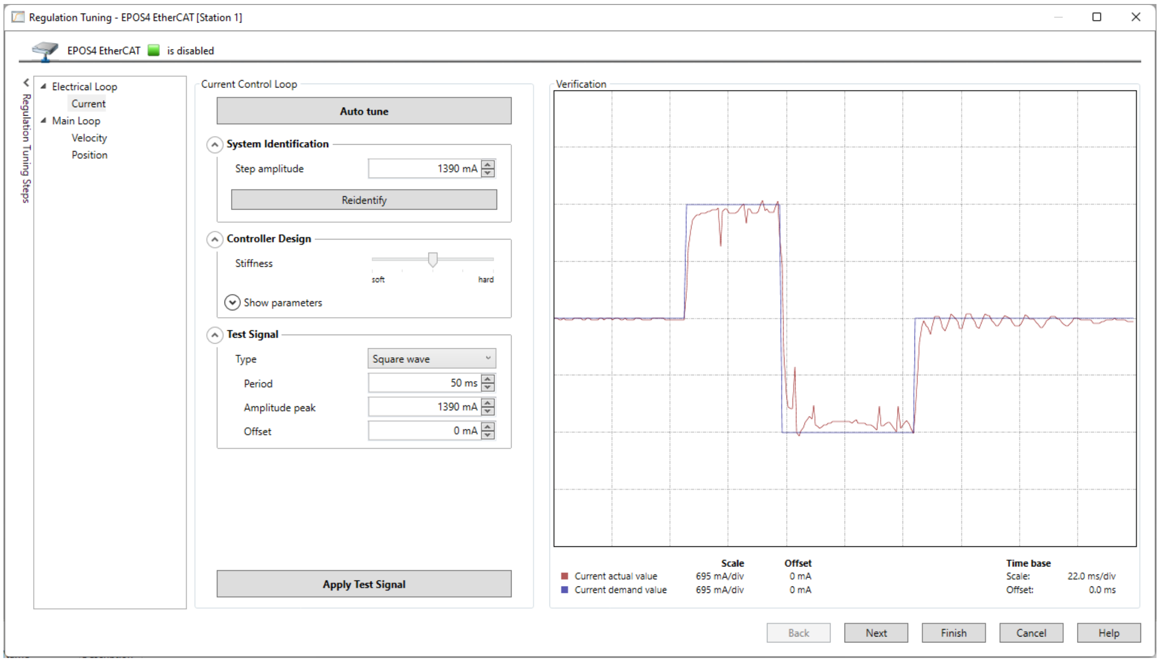
Deceleration: 10000 rpm/s

Actual position: 4 inc

	Scale	Offset
🟥 Position actual value	7 inc/div	-25 inc
🟦 Position demand value	7 inc/div	-25 inc
🟩 Following error actual value	1 inc/div	0.50 inc

Time base
Scale: 271.6 ms/div
Offset: 0.0 ms

Figure 36: Position Tuning, first version.



Current Control Loop

System Identification

Step amplitude 1390 mA

Controller Design

Stiffness

Test Signal

Type: Square wave

Period: 50 ms

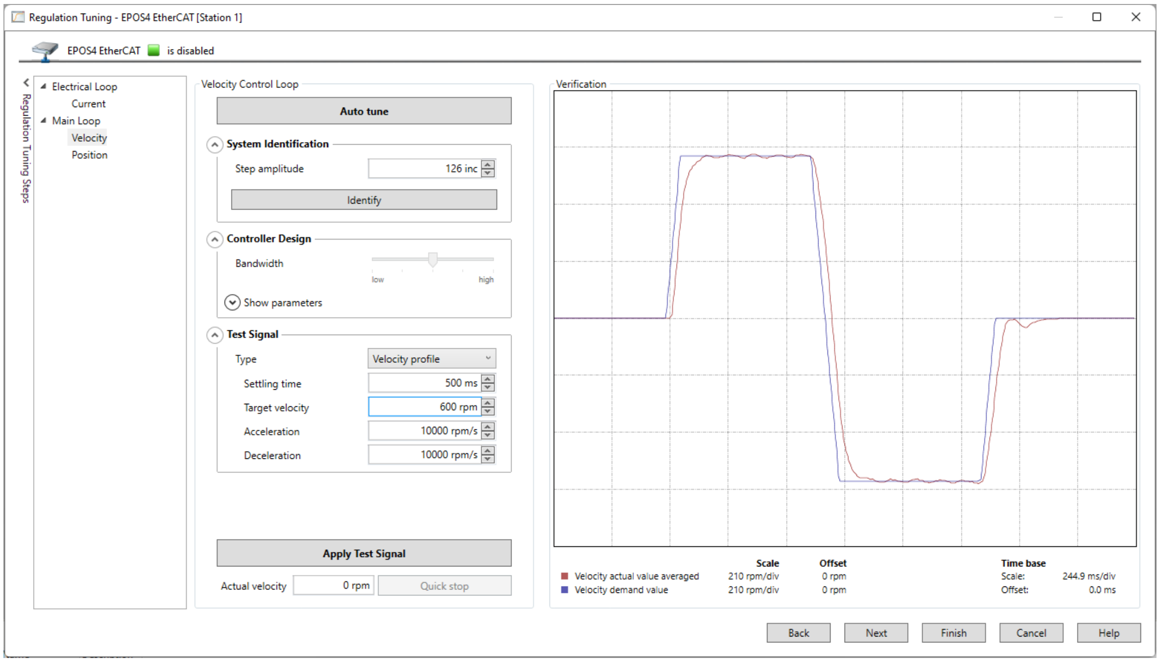
Amplitude peak: 1390 mA

Offset: 0 mA

	Scale	Offset
🟥 Current actual value	695 mA/div	0 mA
🟦 Current demand value	695 mA/div	0 mA

Time base
Scale: 22.0 ms/div
Offset: 0.0 ms

Figure 37: Current Tuning, final version.



Velocity Control Loop

System Identification

Step amplitude 126 inc

Controller Design

Bandwidth

Test Signal

Type: Velocity profile

Settling time: 500 ms

Target velocity: 600 rpm

Acceleration: 10000 rpm/s

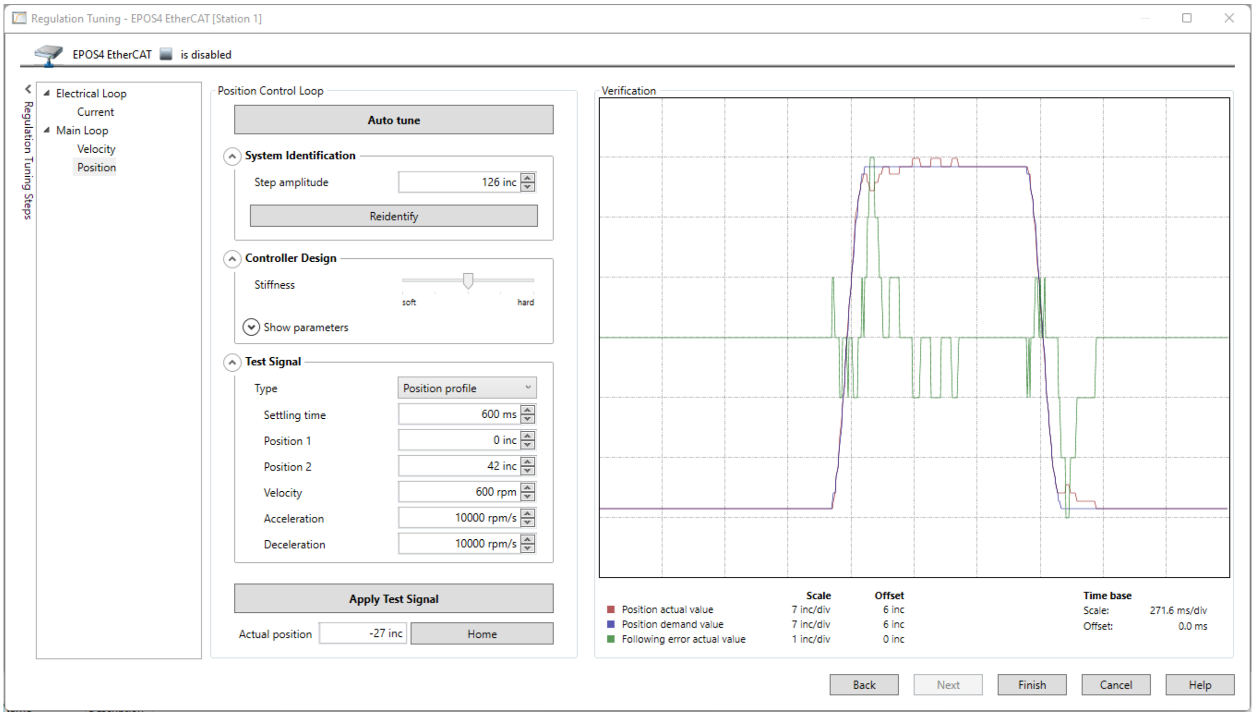
Deceleration: 10000 rpm/s

Actual velocity: 0 rpm

	Scale	Offset
🟥 Velocity actual value averaged	210 rpm/div	0 rpm
🟦 Velocity demand value	210 rpm/div	0 rpm

Time base
Scale: 244.9 ms/div
Offset: 0.0 ms

Figure 38: Velocity Tuning, final version



Step amplitude: 126 inc

Type: Position profile

Settling time: 600 ms

Position 1: 0 inc

Position 2: 42 inc

Velocity: 600 rpm

Acceleration: 10000 rpm/s

Deceleration: 10000 rpm/s

Actual position: -27 inc

	Scale	Offset
🟥 Position actual value	7 inc/div	6 inc
🟦 Position demand value	7 inc/div	6 inc
🟩 Following error actual value	1 inc/div	0 inc

Time base
Scale: 271.6 ms/div
Offset: 0.0 ms

Figure 39: Position Tuning, final version.

5.2 Torque Testing and Results

The principal definition of torque is force times distance; the considered distance is measured from a reference point of origin to the point where the perpendicular force is applied to the body. To test, the motor is fixed at the origin, and a bar is connected to it, working as the torque transmission element. A dynamometer is fixed at a set distance of 25 cm attached to the bar. This instrument will register the value of the force the actuator applies until it gets stuck, allowing the calculation of the actuator's maximum torque capacity or stall torque. Before starting the test, the position angle of the actuator is measured and ensured to be zero (perpendicular to the upcoming force), with a tiltmeter present during all the tests. Also, the dynamometer is set to zero. As shown in **Figure 40**.

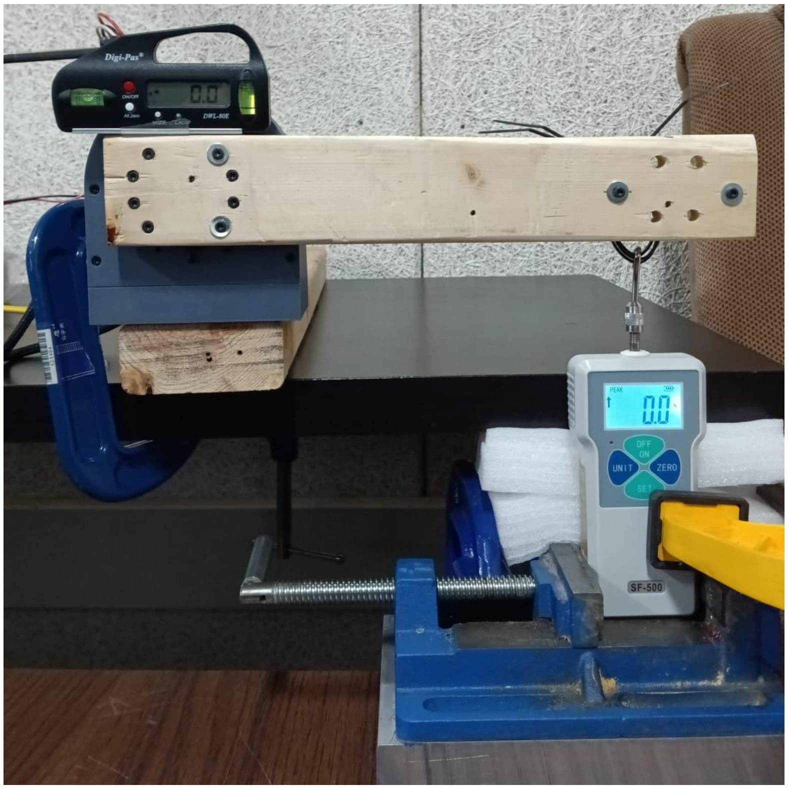


Figure 40: Torque test setup.

To start, a negative angle position target is given to the actuator, which will not be reached as the dynamometer will present resistance to move. In the case of the final version, the brake will be disengaged first. Then, the command to move will be sent, producing a transition from zero to a larger angle and a measure of the maximum force applied. An example of the results of the process can be seen in **Figure 40**: Torque test setup. The results are summarized in **Table 22**. Shows an average stall torque of 44.26 Nm for the first version, an actuator without a brake, and 38.24 Nm for the final version, with a brake. Both results are over the expected theoretical Nominal torque calculated at 28.07 Nm. Also, the difference of 6 Nm of torque between the two versions can be due to the load difference between the shaft and the components attached to it. Version 1 shaft system is simpler and lighter than the final version. The final version has a necessary extra load of 30 gr, considering the brake's hub and the connection part between the harmonic drive and shaft. More testing data are presented in **Appendix K**

Table 22: Test Torque results of version 1, initial design, without brakes, and version 3, model 1, with brakes.

Model	Force (N)	Distance (m)	Equivalent weight applied (kg)	Resulting Stall Torque (Nm)
Initial Version: Without brake, EC60 + SHD 17-100	168.8	0.25	68.83	42.2
	169.8	0.25	69.24	42.45
	178.8	0.25	72.91	44.7
	190.7	0.25	77.76	47.68
Average	**177.025**	**0.25**	**72.18**	**44.26**
Final version with brake: Version 3 - Model 1: EC60 + SHD 17-100 + MBSS13AA	121.5	0.25	49.54	30.38
	152.2	0.25	62.06	38.05
	145.7	0.25	59.41	36.43
	192.4	0.25	78.45	48.1
Average	**152.95**	**0.25**	**62.36**	**38.24**

Table 23: Physical characteristics of the tested models.

Model	Mass (kg)	Outer Dia (mm)	Length (mm)	Hollow Dia (mm)
Initial Version: Without brake, EC60 + SHD 17-100	1.089	80	66.5	12
Final version with brake: Version 3 - Model 1: EC60 + SHD 17-100 + MBSS13AA	1.115	80	83	11.8

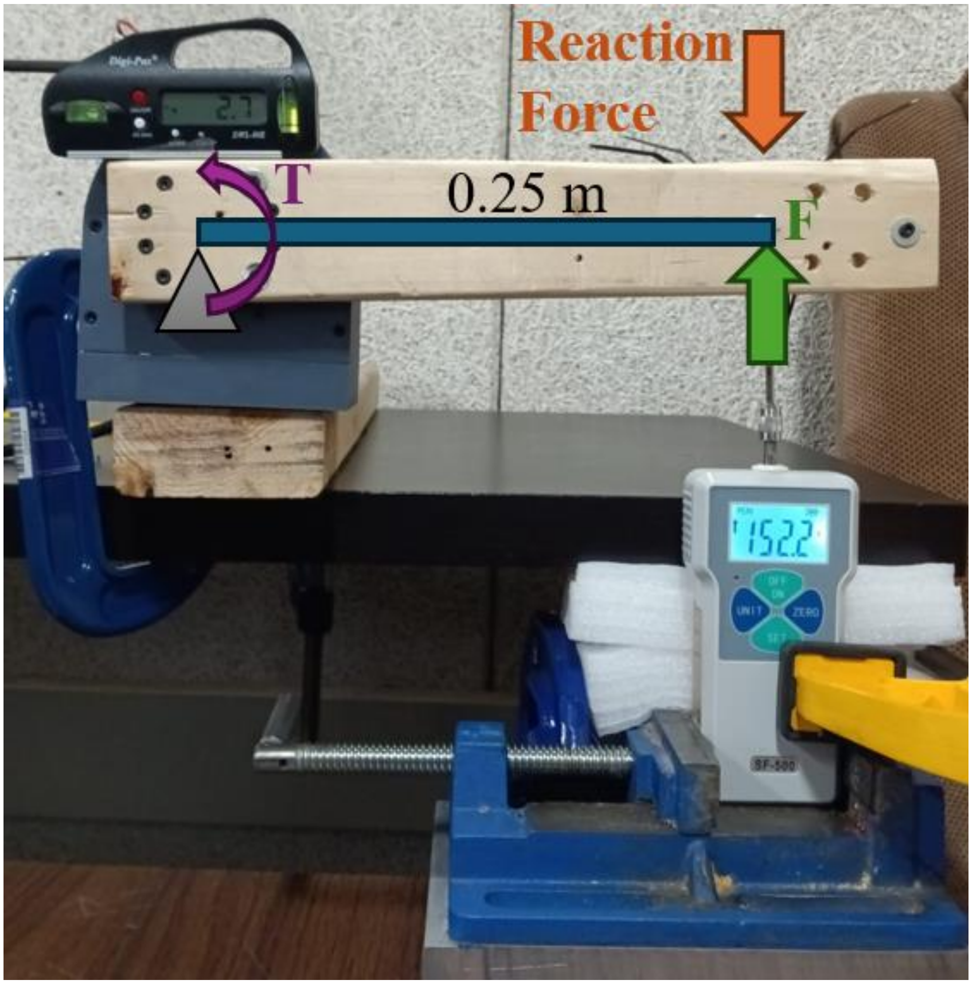


Figure 41: The final stage of the torque test procedure and the final version of the actuator are being tested.

Figure 42: Final and initial version of the custom integrated actuator.

CHAPTER 6

EXPLORATION OF THE BENEFITS OF CUSTOM-DESIGNED ACTUATORS IN A 6-DOF ROBOTIC MANIPULATOR

This chapter presents the definition and characteristics of a wheelchair-mounted robot arm that uses custom integrated actuator joints for ADLs.

6.1 Weight reduction of the existing system, resulting in a new assistive robot arm.

Implementing the thread rings around the actuator's housing can reduce the load of the installation actuator's part to approximately 0.15 kg, an 85% load reduction equivalent to 0.85 kg less. Detailed values are presented in **Table 24**, We can consider that the installation part for the actuator housing used in the mR2A model disappears, actually reducing 1kg out of the system, by considering the mass on the installation rings as part of the mass of the developed integrated actuator joint, which will be compared with the actuator's mass used in the Mr2A. This allows the actuators to allocate the remaining torque to the arm's payload capacity.

Table 24: mR2A: Actuator's fixing part mass.

Location	mR2A Original fixing part mass (gr)	Redesigned fixing part mass (gr)
Link 1	190.21	22.59
Link 2	167.61	22.59
Link 3	155.63	23.17
Link 4	212.29	26.32
Link 5	143.57	26.32
Link 6	127.01	26.32
Total	**996.32**	**147.31**

Furthermore, by reducing the size and mass of the actuator, considering the actuator change in joint 2, more torque capacity could be relocated to the payload capacity. The developed actuators achieve a reduction of 1.825 kg only considering the integrated actuators; adding the remaining 1 kg reduction of installation parts, the weight reduction adds up to 2.825 kg. A detailed description per joint is shown in **Table 25**.

Table 25: 6-DOFs New Assistive robot arm model, integrated actuator joints characteristics.

Joint	Model	Rate torque (Nm)	Hollow Diameter (mm)	Outside Diameter (mm)	Length (mm)	weight (kg)	Driver (kg)	Total weight (kg)
1	EC60 + GHD17	31.9	11.8	80	83	1.115	0.026	1.141
2	EC60 + SHD17	31.9	11.8	80	83	1.115	0.026	1.141
3	EC60 + SHD17	31.9	11.8	80	83	1.115	0.026	1.141
4	EC45 + GHD14	13.4	12	70	71.7	0.8	0.026	0.826
5	EC45 + SHD 14	13.4	12	70	71.7	0.78	0.026	0.806
6	EC45 + SHD 14	13.4	12	70	71.7	0.78	0.026	0.806
					Total	**5.705**	**0.156**	**5.861**

The final characteristics are detailed in **Table 25**, are considering that the tested Stall Torque for EC60 +SHD 17 with brake is 38.24 Nm, and that during the 3kg load testing, the maximum torque register in joint 3 was approximately 37.8 Nm, and in joint 2 it was 31.42 Nm [15].

On the other hand, the change of actuator in joint 2 reduced the outside diameter to 80 mm, originally 90 mm, reducing the inner diameter where the actuator is placed in link 2, and even more, since the installation part is no longer needed that required an inner diameter of 102.9 mm, the inner diameter of the mR2A Link2 is reduced by 22.9 mm, other size reductions are shown in **Table 26**. This size reduction will make link connection parts lighter, too. The total weight reduction can be calculated once the new robot arm links are designed according to the specifications in **Table 26**.

Table 26: Link size, Inner and outer diameter possible reductions.

Link	Inner Diameter of the link (mm)	New inner Diameter (mm)	Reduction (mm)	Outher Diameter (mm)	New Outher Diameter (mm)	Reduction (mm)
1	92.3	80	12.3	100.3	86	14.3
2	102.9	80	22.9	110.3	86	24.3
3	92.3	80	12.3	100.3	86	14.3
4	91.3	70	21.3	99.3	76	23.3
5	83.3	70	13.3	91.3	76	15.3
6	82.3	70	12.3	90.3	76	14.3

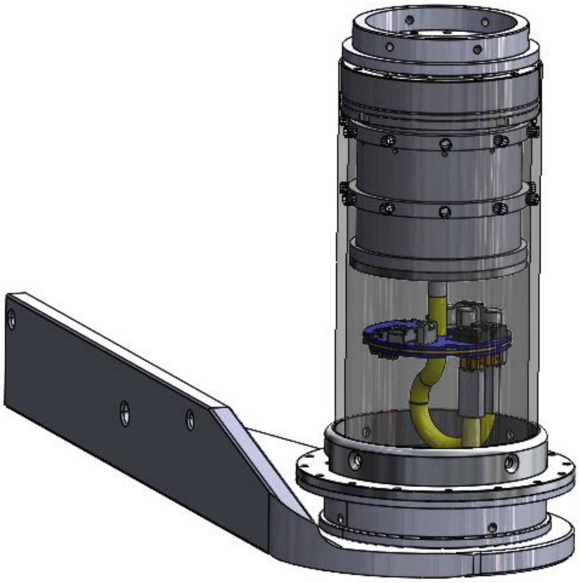


Figure 43: Sample installation of the New Integrated actuator Joint, Joint 1 in Link 1.

6.2 Future Work

Further considerations for a 6-DOF wheelchair-mounted assistive robot arm need to consider the physical characteristics of the new proposed integrated robotic actuator. These can cover the assignment of new Denavit -Hartenberg (DH) parameters.

6.2.1 Denavit -Hartenberg (DH) Parameters Assignment

The 6 DOF manipulator comprises six revolute joints, each giving one DOF. The serial link mechanism relationship is described by the following DH parameters shown in **Table 27**. Also, the homogeneous transformation matrix (HTM), presented in **Equation 5.1**, considers each link's rotation and transformation.

$$T_i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.1}$$

Table 27: Denavit-Hartenberg Parameters of the 6-DOFs Wheelchair Mounted Assistive Robot Arm.

Joint i	$\boldsymbol{a_{i-1}}$	$\boldsymbol{\alpha_{i-1}}$	$\boldsymbol{d_i}$	$\boldsymbol{\theta_i}$
1	0	0	$L_0 + L_1$	θ_1
2	0	$-\pi/2$	0	$\theta_2 + \pi/2$
3	L_2	0	0	θ_3
4	L_3	$\pi/2$	$offset$	θ_4
5	L_4	$-\pi/2$	0	$\theta_5 + \pi/2$
6	0	$\pi/2$	L_5	θ_6

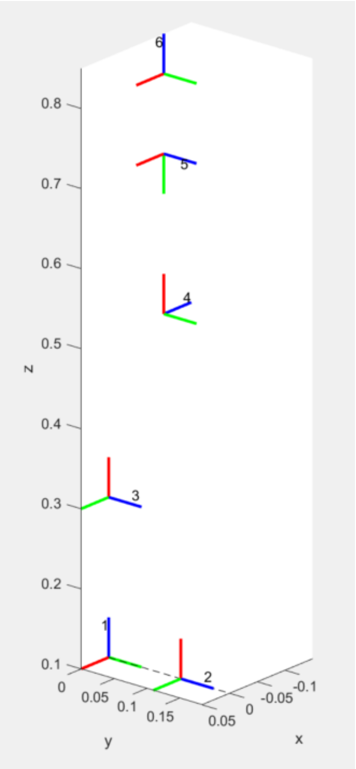


Figure 44: Joint Coordinate Definition and Link Assignment.

Building a prototype with these DH parameters and the new integrated actuators will help test and show their advantages. This prototype can demonstrate how the actuators improve the torque-to-weight ratio, reduce the total weight, and make the design more modular. Testing it in a real environment will prove the benefits of the integrated actuators and their potential to improve the performance and usability of assistive robotic arms. This will also give useful feedback for future improvements and applications.

CHAPTER 7

CONCLUSION AND FUTURE WORKS

The research tackled some of the significant challenges in designing custom-integrated actuators for assistive robotic manipulators. The final prototypes showed clear improvements over existing designs by focusing on compactness, modularity, and efficiency. Notably, the weight reduction in the new assistive robot arm can increase payload capacity and make the actuators more compatible with various power wheelchairs. These advancements mark a significant step forward in creating robotic systems that are both high-performing and user-friendly.

Future efforts should explore new materials and manufacturing techniques to make the actuators even lighter and stronger. Incorporating advanced sensors like force-torque sensors and adaptive control algorithms could also improve safety and responsiveness. Finally, testing these designs in real-world environments will be essential to ensure their reliability and practicality for everyday use. By addressing these areas, technology can take another leap forward, providing users with even greater independence and support.

REFERENCES

[1] Geneva: World Health Organization, "Wheelchair provision guidelines," License: CC BY-NC-SA 3.0 IGO, Jun 2023. [Online]. Available: https://iris.who.int/bitstream/handle/10665/368493/9789240074521-eng.pdf?sequence=1.

[2] Christopher & Dana REEVE FOUNDATION, "Paralysis in the U.S. | Reeve Foundation," Christopher & Dana Reeve Foundation, Nov 2022. [Online]. Available: https://www.christopherreeve.org/todays-care/paralysis-help-overview/stats-about-paralysis/.

[3] World Health Organization, "Assistive Technology," Who.int, 02 Jan. 2024. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/assistive-technology. [Accessed 2024].

[4] E. Muñoz, M. S. H. Sunny, I. Rulik, J. D. S. D. Caro, and M. H. Rahman, "Kinematics and Workspace Analysis of xArm6 Robot for Activities of Daily Living," Proceedings. International Conference on Industrial & Mechanical Engineering and Operations Management, 2021. [Online]. Available: Available: https://www.semanticscholar.org/paper/Kinematics-and-Workspace-Analysis-of-xArm6-Robot-of-Mu%C3%B1oz-Sunny/95ecc3d45b9ace0b3facfccd8497ffbebb5e70e4.

[5] Centers for Disease Control and Prevention, "Caregiving for Family and Friends: a Public Health Issue," Centers for Disease Control and Prevention, 07 Aug 2019. [Online]. Available: https://www.cdc.gov/aging/caregiving/caregiver-brief.html.

[6] CDC, "Supporting Caregivers | CDC," Center for Disease Control and Prevention, 01 Sep 2022. [Online]. Available: https://www.cdc.gov/aging/publications/features/supporting-caregivers.htm#:~:text=The%20number%20of%20caregivers%20increased.

[7] CDC, "Disability and Health Healthcare Cost Data | CDC," 16 Nov 2018. [Online]. Available: https://www.cdc.gov/ncbddd/disabilityandhealth/data-highlights.html.

[8] CMS, "CMS office of the actuary releases 2021-2030 projections of national health expenditures | CMS," Centers for Medicare & Medicaid Services, 28 Mar 2022. [Online]. Available: https://www.cms.gov/newsroom/press-releases/cms-office-actuary-releases-2021-2030-projections-national-health-expenditures.

[9] T. Z. a. B. S. D. Shanmugam Muruga Palaniappan, "Identifying Comfort Areas in 3D Space for Persons with Upper Extremity Mobility Impairments Using Virtual Reality," Oct 2019. [Online]. Available: doi: https://doi.org/10.1145/3308561.3353810..

[10] M. Faizullabhoy and Shishanka Wangnoo, "Wheelchair Mounted Robotic Arm Market - By Application (Spinal Cord Injury, Neurological Conditions), 2023 – 2032," Global Market Insights Inc., 2023. [Online]. Available: https://www.gminsights.com/industry-analysis/wheelchair-mounted-.

[11] K. D. Edwards, "Design, Construction and Testing of a Wheelchair-Mounted Robotic Arm," USF Tampa Graduate Theses and Dissertations., 2005. [Online]. Available: https://digitalcommons.usf.edu/etd/2867.

[12] Schrock, Peter J., "Design and Testing of a Lightweight Modular Seven-Degree-of-Freedom Robot Arm for Mobile Use," USF Tampa Graduate Theses and Dissertations, 2008. [Online]. Available: https://digitalcommons.usf.edu/etd/489.

[13] German Aerospace Center (DLR), "Mechatronic design of the LWR III," Institute of Robotics and Mechatronics, [Online]. Available: www.dlr.de. https://www.dlr.de/en/rm/research/robotic-systems/arms/lwr-iii/mechatronic-design-of-the-lwr-iii.

[14] DLR Institute of Robotics and Mechatronics, "LWR I (1991–1996)," www.dlr.de, 2024. [Online]. Available: https://www.dlr.de/en/rm/research/robotic-systems/arms/lwr-i-1991-1996.

[15] J. D. Sanjuan De Caro, "Methodology for Designing Assistive Robots for Activities of Daily Living Assistance," Order No. 30529910, The University of Wisconsin - Milwaukee, United States -- Wisconsin, 2023.

[16] Kinova - Assistive Technologies, "Robotic arm," 2021. [Online]. Available: https://assistive.kinovarobotics.com/product/jaco-robotic-arm#ProductSpecsOverview.

[17] Assistive Innovations, "Assistive Innovations - iARM," www.assistive-innovations.com, 2024. [Online]. Available: https://www.assistive-innovations.com/en/robotic-arms/iarm.

[18] ACCREA Engineering, "BATEO – ACCREA Engineering," Accrea.com, 2024. [Online]. Available: https://accrea.com/bateo/.

[19] ACCREA Engineering, "ARIA – ACCREA Engineering," Accrea.com, 2024. [Online]. Available: https://accrea.com/aria/.

[20] Z. Yuan, "Current status and prospects of actuator in robotics," in *Applied and Computational Engineering*, vol. 11, no. 1, pp. 181–191, Sep. 2023 , doi: https://doi.org/10.54254/2755-2721/11/20230232..

[21] ZeroErr, "eRob 70I-ZeroErr eRob 70I Rotary Actuator," Zeroerr.cn, 2024. [Online]. Available: https://en.zeroerr.cn/rotary_actuators/erob70i.

[22] ROBOTIS, "ROBOTIS: DYNAMIXEL PRO," ROBOTIS e-Manual, 2024. [Online]. Available: https://emanual.robotis.com/docs/en/dxl/pro/ .

[23] ZeroErr, "eRob 70T-ZeroErr eRob 70T Rotary Actuator," Zeroerr.cn, 2024. [Online]. Available: https://en.zeroerr.cn/rotary_actuators/erob70t.

[24] W.-K. Song, H. Lee, and Z. Bien,, "KARES: Intelligent wheelchair-mounted robotic arm system using vision and force sensor," Robotics and Autonomous Systems, vol. 28, no. 1, pp. 83–94, Jul 1999. [Online]. Available: doi: https://doi.org/10.1016/s0921-8890(99)00031-7..

[25] B. Driessen, H. Evers, and J. v Woerden, "Manus—a wheelchair-mounted rehabilita tion robot," Proceedings of the Institution of Mechanical Engineers, Part H: Journal of engineering in medicine, vol. 215, no. 3, pp. 285–290, 2001. [Online].

[26] M. Hillman, K. Hagan, S. Hagan, J. Jepson, and R. Orpwood, "The Weston wheelchair mounted assistive robot - the design story," Robotica, vol. 20, no. 2, pp. 125–132, Mar 2002. [Online]. Available: doi: https://doi.org/10.1017/s0263574701003897..

[27] Z. Bien, D.-J. Kim, M.-J. Chung, D.-S. Kwon, and Pyung Hun Chang, "Development of a wheelchair-based rehabilitation robotic system (KARES II) with various human-robot interaction interfaces for the disabled," Mar 2004. [Online]. Available: doi: https://doi.org/10.1109/aim.20.

[28] Grigorescu, Sorin M., et al., "A BCI-Controlled Robotic Assistant for Quadriplegic People in Domestic and Professional Life," Robotica, vol. 30, no. 3, pp. 419–431, 1 May 2012. [Online]. Available: www.cambridge.org/core/journals/robotica/article/bcicontrolled-robotic-assistan.

[29] U. Reiser, R. Volz, F. Geibel, and Fraunhofer IPA, "ManIPA: A flexible Manipulation Framework for Collision Avoidance and Robot Control.," 2016. [Online]. Available: https://www.researchgate.net/publication/237143730.

[30] M. Kyrarini et al., "A Survey of Robots in Healthcare," Technologies, vol. 9, no. 1, p. 8, Jan 2021. [Online]. Available: doi: https://doi.org/10.3390/technologies9010008..

[31] KINOVA, "Discover Our Gen2 Robots," Kinova, 2013. [Online]. Available: https://www.kinovarobotics.com/product/gen2-robots.

[32] KINOVA, "Discover our Gen3 robots," Kinova, 2018. [Online]. Available: https://www.kinovarobotics.com/product/gen3-robots.

[33] KINOVA, "Discover our Gen3 lite robo," Kinova, 2019. [Online]. Available: https://www.kinovarobotics.com/product/gen3-lite-robots.

[34] S. Leone et al., "Design of a Wheelchair-Mounted Robotic Arm for Feeding Assistance of Upper-Limb Impaired Patients," Robotics, vol. 13, no. 3, p. 38, Mar 2024. [Online]. Available: doi: https://doi.org/10.3390/robotics13030038.

[35] Edwards, Kevin D., "Design, Construction and Testing of a Wheelchair-Mounted Robotic Arm," USF Tampa Graduate Theses and Dissertations., 2005. [Online]. Available: https://digitalcommons.usf.edu/etd/2867.

[36] S. Rader, L. Kaul, H. Fischbach, Nikolaus Vahrenkamp, and T. Asfour, "Design of a high-performance humanoid dual arm system with inner shoulder joints," Nov 2016. [Online]. Available: doi: https://doi.org/10.1109/humanoids.2016.7803325.

[37] Kim H, Miller LM, Al-Refai A, Brand M, Rosen J, "Redundancy resolution of a human arm for controlling a seven DOF wearable robotic system," Kim H, Miller LM, Al-Refai A,Annu Int Conf IEEE Eng Med Biol Soc. 2011;2011:3471-4. doi: 10.1109/IEMBS.2011.6090938. PMID: 22255087..

[38] International Organization for Standardization, "Earth-moving machinery — Physical dimensions of operators and minimum operator space envelope," ISO 3411:2007, 2021. [Online]. Available: https://www.iso.org/standard/38911.html.

[39] E. Muñoz et al., "Effects of the Link Lengths in the Design and Optimization of A 6 DOF Assistive Robot for Activities of Daily Living," Proceedings of the 9th International Conference of Control Systems, and Robotics (CDSR'22), Jun 2022. [Online]. Available: doi: https://doi.org/10.11159/cdsr22.111..

[40] J. D. Sanjuan De Caro and et al., "Evaluation of Objective Functions for the Optimal Design of an Assistive Robot," Micromachines, vol. 13, no. 12, pp. 2206–2206, Dec 2022. [Online]. Available: doi: https://doi.org/10.3390/mi13122206..

[41] P. F. Edemekong, D. L. Bomgaars, and S. B. Levy, "Activities of Daily Living (ADLs)," NCBI, 26 Jun 2023. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK470404/.

[42] M. S. Haque Sunny et al., "Identification of the Workspaces of Essential Activities of Daily Living for a Wheelchair-mounted Robotic Arm," 2024 ACRM Annual Fall Conference & EXPO, 01 Nov 2024. [Online]. Available: https://acrm2024.eventscribe.net/fsPopup.asp?PosterID=676385&mode=posterInfo.

[43] M. M. Rahman et al., "Development of a Three-Finger Adaptive Robotic Gripper to Assist Activities of Daily Living,," Designs, vol. 8, no. 2, pp. 35–35, Apr 2024. [Online]. Available: doi: https://doi.org/10.3390/designs8020035..

[44] Medicare, "LCD - Power Mobility Devices (L33789)," www.cms.gov, 16 May 2023. [Online]. Available: https://www.cms.gov/medicare-coverage-database/view/lcd.aspx?LCDId=33789.

[45] Freedom Mobility, "What is a Bariatric Electric Wheelchair?," Freedomhme.com, 2022. [Online]. Available: https://www.freedomhme.com/blog/post/what-is-a-bariatric-electric-wheelchair-.

[46] Department of Justice, "2010 ADA Standards for Accessible Design," U.S. Department of Justice Civil Rights Division, 15 Sep 2010. [Online]. Available: https://www.ada.gov/assets/pdfs/2010-design-standards.pdf.

[47] 1800WheelChair, "What is The Average Size of an Electric Wheelchair? - Wheelchair & Mobility Scooters Guide," Wheelchair & Mobility Scooters Guide, 07 Aug 2024. [Online]. Available: https://www.1800wheelchair.com/news/what-is-the-average-size-of-a-electric-wheelchair/.

[48] J. D. Sanjuan De Caro, Md. S. H. Sunny, E. J. M. Montenegro, H. U. Ahmed, and M. H. Rahman, "Optimal Base Placement of a 6-DOFs Robot to Cover Essential Activities of Daily Living," IEEE Access, vol. 10, pp. 134536–134548, 2022. [Online]. Available: doi: https://doi.org/10.1109.

[49] P. I. Corke, "A Simple and Systematic Approach to Assigning Denavit–Hartenberg Parameters," IEEE Transactions on Robotics, vol. 23, no. 3, pp. 590-594, June 2007, doi: 10.1109/TRO.2007.896765.

[50] MAXON, "Drive systems for robotics. High torque, compact and efficient," Precision Drive Systems, 2024. [Online]. Available: https://7157e75ac0509b6a8f5c-5b19c577d01b9ccfe75d2f9e4b17ab55.ssl.cf1.rackcdn.com/QILFJRYH-PDF-6-516962-4481839787.pdf.

[51] V. Popov, A. V. Topalov, T. Stoyanov, and S. Ahmed-Shieva, "Kinematic Modeling with Experimental Validation of a KUKA®–Kinova® Holonomic Mobile Manipulator," Electronics, vol. 13, no. 8, p. 1534, Apr. 2024. [Online]. Available: doi: https://doi.org/10.3390/electronics13081534.

[52] E. Engler Modic, "User-FRIENDly Rehabilitation Robot," Todaysmedicaldevelopments.com, 24 Aug 2010. [Online]. Available: https://www.todaysmedicaldevelopments.com/article/tmd-0810-user-friendly-rehabilitation-robot/.

[53] SCHUNK, "UNIVERSAL ROTARY ACTUATOR PRL," SCHUNK, 2008. [Online]. Available: https://www.cs.unc.edu/Research/stc/FAQs/Schunk/old-irrelevant/PRL_Manual_V01.pdf.

[54] Rozum, "Servomotors RDrive | Rozum Robotics," Rozum Robotics LLC. , 2024. [Online]. Available: https://rozum.com/servomotors/#about.

[55] Igus, "Cost-effective and compact: gearbox system for service robotics," ReBeL, 2024. [Online]. Available: https://www.igus.ie/info/rebel-gearbox-system.

[56] Nikon, "Nikon expands lineup of C3 eMotion intelligent actuator units for robotic joints used in collaborative robot | News | Nikon About Us," Nikon, 2024. [Online]. Available: https://www.nikon.com/company/news/2022/0303_encoder_01.html.

[57] ZeroErr, "ZeroErr eRob Rotary Actuators Series," Zeroerr.cn, 2024. [Online]. Available: https://en.zeroerr.cn/rotary_actuators.

[58] Z. Ledy, "eRob Robot Joint Module," Zhengzhou Defy Mechanical&Electrical Equipment Co. Ltd., 2024. [Online]. Available: https://metonec.com/product/eRob-Robot-Joint-Module/ .

[59] Laifual Group, "High Voltage Rotary Actuators MIS Series-Laifual," Laifual Group, 2024. [Online]. Available: https://www.laifualgroup.com/product/high-voltage-rotary-actuators-mis-series.html.

[60] ROBOTIS, "DYNAMIXEL PM54-040-S250-R," ROBOTIS, 2024. [Online]. Available: https://www.robotis.us/dynamixel-pm54-040-s250-r/ (accessed Nov. 10, 2024)..

[61] ROBOTIS, "YM080-230-R051-RH," DYNAMIXEL-Y, 2024. [Online]. Available: https://www.robotis.us/ym080-230-r051-rh/.

[62] ROBOTIS, "DYNAMIXEL-Y - ROBOTIS," Robotis.us, 2024. [Online]. Available: https://www.robotis.us/dynamixel-y/.

[63] Sierramotion, "SMRT-2000 Robot Joint | Integrated Drive Train," Sierramotion, 19 May 2023. [Online]. Available: https://www.sierramotion.com/products/mechatronic-assemblies/smrt-2000-robot-joint/#introduction.

[64] Roboct, "Integrated Robot Joint Module," Roboct-global.com, 2017. [Online]. Available: https://www.roboct-global.com/robot-core-components/robot-joint-module/integrated-robot-joint-module.html.

[65] TONIFISHI, "HJ14-TONIFISHI-Provider Of Precision Transmission Solutions," Tonifishi.com, 2024. [Online]. Available: https://www.tonifishi.com/productinfo/1187890.html.

[66] TONIFISHI, "PH14-TONIFISHI-Provider Of Precision Transmission Solutions," Tonifishi.com, 2024. [Online]. Available: https://www.tonifishi.com/productinfo/1181390.html.

[67] Sumitomo Drive Thecnologies, "Sumitomo Drive Actuators | Advanced Motion Control Solutions," Sumitomodrive.com, 2024. [Online]. Available: https://us.sumitomodrive.com/en-us/motion-control/actuators .

[68] MAXON, "Robotics Drives - Products and Services," Maxongroup.com, 2024. [Online]. Available: https://www.maxongroup.com/assets/public/caas/v1/media/247410/data/a8da7a323e29e16421fcd5c4280f0102/whitepaper-flyer-robotics-products-and-services-en.pdf.

[69] ZeroErr, "eRob 70F-ZeroErr eRob 70F Rotary Actuator," Zeroerr.cn, 2024. [Online]. Available: https://en.zeroerr.cn/rotary_actuators/erob70f .

[70] D. Norman, "The Design of Everyday Things: Revised and Expanded Edition.," 2013. [Online]. Available: https://www.hachettebookgroup.com/titles/don-norman/the-design-of-everyday-things/9780465050659/?lens=basic-books.

[71] D. Meadows, "Thinking in Systems," 2008. [Online]. Available: https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/climate-communications/psychology-amp-behavior/Meadows-2008.-Thinking-in-Systems.pdf.

[72] F. K. Y. Chan and J. Y. L. Thong, "Acceptance of agile methodologies: A critical review and conceptual framework," Decision Support Systems, vol. 46, no. 4, pp. 803–814, Mar 2019. [Online]. Available: doi: https://doi.org/10.1016/j.dss.2008.11.009..

[73] K. S. Rubin, "Essential Scrum: A Practical Guide to the Most Popular Agile Process," Upper Saddle River, NJ: Addison-Wesley, 2012. [Online]. Available: https://libdoc.dpu.ac.th/eBook/113642.pdf. .

[74] A. N. Arnette, B. L. Brewer, and T. Choal, "Design for sustainability (DFS): the intersection of supply chain and environment," Journal of Cleaner Production, vol. 83, pp. 374–390, ISSN 0959-6526, Nov 2014. [Online]. Available: doi: https://doi.org/10.1016/j.jclepro.2014.07.021.

[75] S. Walker, "Sustainable by Design: Explorations in Theory and Practice," (1st ed.). Routledge, 2006. [Online]. Available: DOI: https://doi.org/10.4324/9781849772747.

[76] M. Johnson, "Engineering a More Sustainable Future," ASME FOUNDATION, Voices, 1 July 2022. [Online]. Available: https://www.asmefoundation.org/2022/07/01/engineering-a-more-sustainable-future/.

[77] J. G. Bralla, "Design for Manufacturability Handbook," AccessEngineering | McGraw-Hill Education - Access Engineering, 1999. [Online]. Available: https://www.accessengineeringlibrary.com/binary/mheaeworks/03f486c4689e37d6/d9932f0a4f01b04de811b6587c2bfb5a538ed30b94f651b6a9c83456b8ed6ca4/book-summary.pdf.

[78] MAXON, "The maxon quality mindset | maxon group," www.maxongroup.com., 2024. [Online]. Available: https://www.maxongroup.com/en-us/company/quality.

[79] MAXON, "Installation Manual," Mar. 2021. [Online]. Available: https://www.maxongroup.com/medias/sys_master/root/8873283846174/ecXXframeless-en-21-03.pdf.

[80] MAXON, "Online shop for high precise drive systems by maxon | maxon group 550154," www.maxongroup.com, 2024. [Online]. Available: https://www.maxongroup.com/maxon/view/product/550154.

[81] MAXON, "Online shop for high precise drive systems by maxon | maxon group," 574037, www.maxongroup.com, 2024. [Online]. Available: https://www.maxongroup.com/maxon/view/product/574037.

[82] International Organization for Standardization, "ISO 10218-1:2011(en) Robots and Robotic Devices Safety Requirements for Industrial Robots — Part 1: Robots," Iso.org, 2011. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:iso:10218:-1:ed-2:v1:en.

[83] MAXON, "Hardware Reference: EPOS4 Disk 60/8," 2021. [Online]. Available: https://www.maxongroup.com/medias/sys_master/root/8934669680670/EPOS4-Disk-60-8-Hardware-Reference-En.pdf.

[84] G. Cena, I. C. Bertolotti, A. Valenzano and C. Zunino, "A high-performance CAN-like arbitration scheme for EtherCAT," 2009 IEEE Conference on Emerging Technologies & Factory Automation, Palma de Mallorca, Spain, 2009, pp. 1-8, doi: 10.1109/ETFA.2009.53470 . [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5347000?casa_token=RP6VAu_LU4oAAAAA:bbo-fxG0YPDhSMGTBuR8Y5sIswwmw6kiZ8IwQvX4omU9n12ue_30g5XE28_hgHS1nnijv1QaB8aVUkI.

[85] 3F FAMED, "SHD Series Component Set Of Harmonic Gearbox- Fenghua Transmission Technology (Jiangsu) Co., Ltd.," www.3fgearbox.com , 2024. [Online]. Available: https://www.3fgearbox.com/shd-series-component-set-of-harmonic-gearbox.html.

[86] GIGAGER Precision Technology Co., Ltd., "China High Quality GHD-I Manufacturers, Suppliers, Factory - SAINI," www.gigager.net., 2024. [Online]. Available: https://www.gigager.net/harmonic-drive-gearbox/ghd-series/ghd-i.html.

[87] Chain Tail, "MBS Ultra Thin Brake - Overexcitation," Chain Tail Co., Ltd., 2024. [Online]. Available: https://www.chaintail.com/mbs-ultra-thin-brake-overexcitation.html.

[88] JTEKT CORPORATION, "Koyo Bearings / JTEKT CORPORATION," koyo.jtekt.co.jp. , 2024. [Online]. Available: https://koyo.jtekt.co.jp/en/products/detail/?pno=6703%202RS.

[89] JTEKT CORPORATION, "Deep Groove Ball Bearings/Product Information/Koyo Bearings (JTEKT)," koyo.jtekt.co.jp, 2024. [Online]. Available: https://koyo.jtekt.co.jp/en/products/type/deep-groove-ball-bearing/.

[90] AMAZON, "1PCS Bearing 6703 17X23X4 6703ZZ 6703Z 6703RS 6703-2RS Single Row Deep Groove Ball Bearings Metric Thin Wall Bearings (Color : 6703-2RS): Amazon.com: Industrial & Scientific," Amazon.com, 12 Nov 2024. [Online]. Available: https://www.amazon.com/Bearing-17X23X4-6703ZZ-6703-2RS-Bearings/dp/B0CNR1Q7GG?th=1.

[91] S. Bai, X. Li, Z. Xie, Z. Zhou, and J. Ou, "A Wireless Fatigue Monitoring System Utilizing a Bio-Inspired Tree Ring Data Tracking Technique," Sensors, vol. 14, no. 3, pp. 4364–4383, Mar 2014. [Online]. Available: doi: https://doi.org/10.3390/s140304364..

[92] Y. Cai et al, "Motor and Physical Function Impairments as Contributors to Slow Gait Speed and Mobility Difficulty in Middle-Aged and Older Adults," vol. 77, no. 8, pp. 1620-1628, Jan 2022. [Online]. Available: doi: https://doi.org/10.1093/gerona/glac001.

[93] S. W. Brose et al, "The role of assistive robotics in the lives of persons with disability," American Journal of Physical Medicine & Rehabilitation, vol. 89, no. 6, pp. 509–521, Jun 2010. [Online]. Available: Doi: https://doi.org/10.1097/PHM.0b013e3181cf569b.

[94] Rozum, "Servomotors RDrive | Rozum Robotics,," Rozum Robotics LLC, 2024. [Online]. Available: https://rozum.com/servomotors/#about.

[95] Rebel, "ReBel fully integrated shaft gearbox - size 105," rbtx.com, 2024. [Online]. Available: https://rbtx.com/en-US/components/accessories/rebel-fully-integrated-shaft-gearbox-size-105.

[96] eRob, "Robot Joint Actuator Module For Jointed Arm Robot Erob 70 Joint Servo Motor - Buy Robot Joint Actuator jointed Arm Robot joint Servo Motor Product on Alibaba.com," eRob, 2024. [Online]. Available: https://www.alibaba.com/product-detail/Robot-Joint-Actuator-module-for-jointed_1600600665751.html.

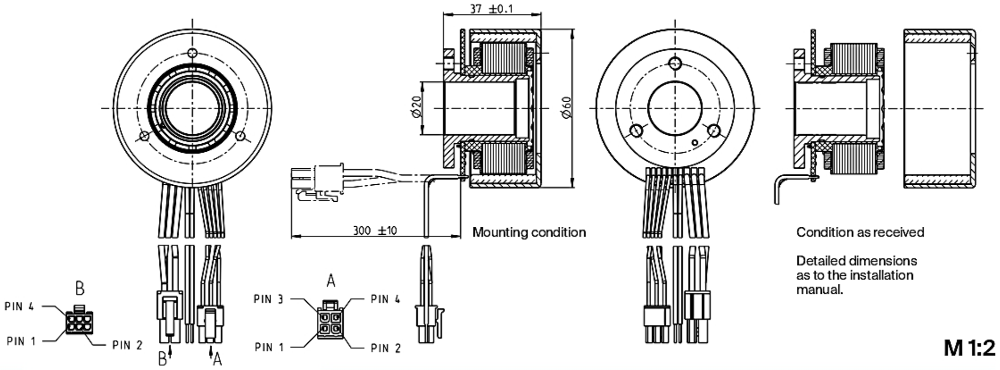
[97] Maxon Motor, "maxon Product Range 2024/25," Maxon Motor, 2024. [Online]. Available: https://online.flippingbook.com/view/1042987/560/?sharedOn=.

[98] Sierramotion, "SMRT-2000 Robot Joint | Integrated Drive Train," Sierramotion, 2024. [Online]. Available: https://www.sierramotion.com/products/mechatronic-assemblies/smrt-2000-robot-joint/.

[99] ZerroErr, "eRob 170I Rotary Actuator," en.zeroerr.cn, 2024. [Online]. Available: https://en.zeroerr.cn/rotary_actuators/erob170i.

Appendix A EC Frameless 60 flat Maxon Motor data

EC frameless 60 flat ∅60 mm, brushless, 100 watt



🟥 Stock program
☐ Standard program
▨ Special program (on request)

Part Numbers

			550153	542002	550154
	with Hall sensors				
Motor Data					
	Values at nominal voltage				
1	Nominal voltage	V	12	24	48
2	No load speed	rpm	3710	4250	3970
3	No load current	mA	671	419	187
4	Nominal speed	rpm	3170	3740	3490
5	Nominal torque (max. continuous torque)	mNm	279	289	319
6	Nominal current (max. continuous current)	A	9.25	5.47	2.78
7	Stall torque	mNm	2850	4180	5010
8	Stall current	A	93.5	78.2	43.8
9	Max. efficiency	%	84	86	88
	Characteristics				
10	Terminal resistance phase to phase	Ω	0.128	0.307	1.1
11	Terminal inductance phase to phase	mH	0.062	0.188	0.864
12	Torque constant	mNm/A	30.5	53.4	114
13	Speed constant	rpm/V	313	179	83.4
14	Speed/torque gradient	rpm/mNm	1.32	1.03	0.798
15	Mechanical time constant	ms	17.2	13.4	10.4
16	Rotor inertia	gcm^2	1246	1246	1246

Specifications

	Thermal data	
17	Thermal resistance housing-ambient	2.5 K/W
18	Thermal resistance winding-housing	3.8 K/W
19	Thermal time constant winding	40 s
20	Thermal time constant motor	89.9 s
21	Ambient temperature	-40...+100°C
22	Max. winding temperature	+125°C
	Mechanical data	
23	Max. speed	6000 rpm
	Other specifications	7
29	Number of pole pairs	3
30	Number of phases	333 g
31	Weight of motor	160 g
	Weight of rotor	173 g
	Weight of stator	

Values listed in the table are nominal.

Connection motor (Cable AWG 18)

red	Motor winding 1	Pin 1
black	Motor winding 2	Pin 2
white	Motor winding 3	Pin 3
	N.C.	Pin 4

Connector	**Part number**
Molex	39-01-2040

Connection sensors (Cable AWG 24)

yellow	Hall sensor 1	Pin 1
brown	Hall sensor 2	Pin 2
grey	Hall sensor 3	Pin 3
blue	GND	Pin 4
green	V_{Hall} 4.5...24 VDC	Pin 5
	N.C.	Pin 6

Connector	**Part number**
Molex	43025-0600

Wiring diagram for Hall sensors see p. 59

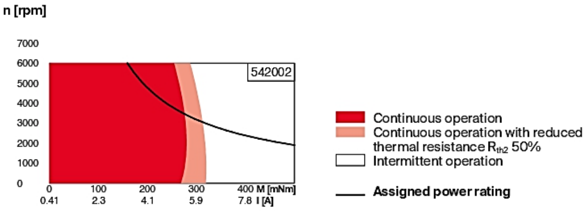
Connection NTC (Cable AWG 24)

pink	NTC
blue	NTC

Resistance 25°C: 5 kΩ ±1%, beta(25–85°C): 3490 K

Operating Range

Comments



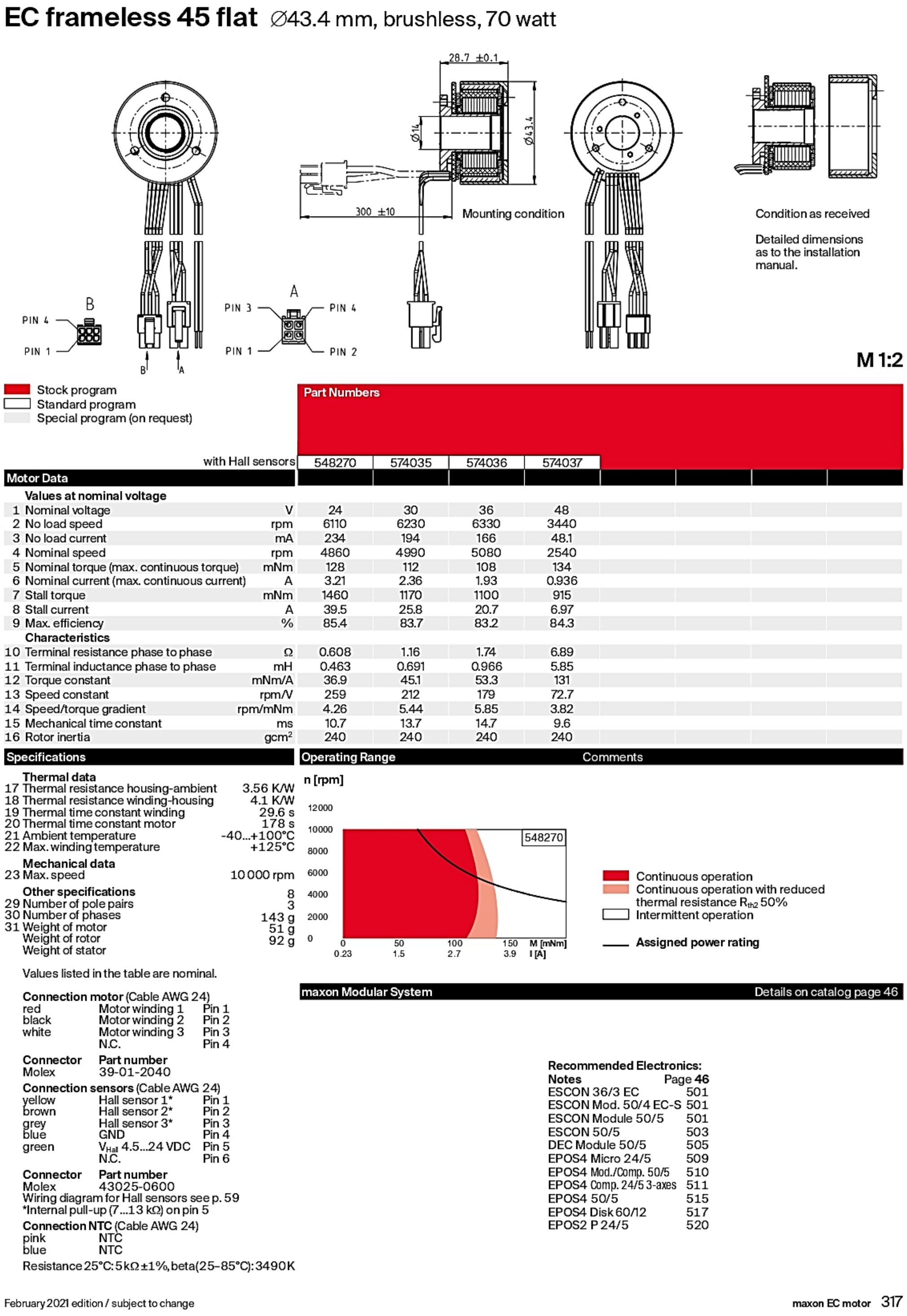
maxon Modular System Details on catalog page 46

Recommended Electronics:

Notes	Page **46**
ESCON Mod. 50/4 EC-S	501
ESCON Mod. 50/5	501
ESCON Mod. 50/8 (HE)	502
ESCON 50/5	503
ESCON 70/10	503
DEC Module 50/5	505
EPOS4 Mod./Comp. 50/5	510
EPOS4 Mod./Comp. 50/8	513
EPOS4 50/5	515
EPOS4 70/15	515
EPOS4 Disk 60/8	516
EPOS4 Disk 60/12	517
EPOS2 P 24/5	520

Reproduce from [80].

Appendix B EC Frameless 45 flat Maxon Motor Data



EC frameless 45 flat ∅43.4 mm, brushless, 70 watt

Mounting condition

Condition as received

Detailed dimensions as to the installation manual.

EC frameless

M 1:2

🟥 Stock program
☐ Standard program
Special program (on request)

Part Numbers

		with Hall sensors	548270	574035	574036	574037
Motor Data						
	Values at nominal voltage					
1	Nominal voltage	V	24	30	36	48
2	No load speed	rpm	6110	6230	6330	3440
3	No load current	mA	234	194	166	48.1
4	Nominal speed	rpm	4860	4990	5080	2540
5	Nominal torque (max. continuous torque)	mNm	128	112	108	134
6	Nominal current (max. continuous current)	A	3.21	2.36	1.93	0.936
7	Stall torque	mNm	1460	1170	1100	915
8	Stall current	A	39.5	25.8	20.7	6.97
9	Max. efficiency	%	85.4	83.7	83.2	84.3
	Characteristics					
10	Terminal resistance phase to phase	Ω	0.608	1.16	1.74	6.89
11	Terminal inductance phase to phase	mH	0.463	0.691	0.966	5.85
12	Torque constant	mNm/A	36.9	45.1	53.3	131
13	Speed constant	rpm/V	259	212	179	72.7
14	Speed/torque gradient	rpm/mNm	4.26	5.44	5.85	3.82
15	Mechanical time constant	ms	10.7	13.7	14.7	9.6
16	Rotor inertia	gcm^2	240	240	240	240

Specifications

	Thermal data	
17	Thermal resistance housing-ambient	3.56 K/W
18	Thermal resistance winding-housing	4.1 K/W
19	Thermal time constant winding	29.6 s
20	Thermal time constant motor	178 s
21	Ambient temperature	-40...+100°C
22	Max. winding temperature	+125°C
	Mechanical data	
23	Max. speed	10 000 rpm
	Other specifications	
29	Number of pole pairs	8
30	Number of phases	3
31	Weight of motor	143 g
	Weight of rotor	51 g
	Weight of stator	92 g

Values listed in the table are nominal.

Connection motor (Cable AWG 24)

red	Motor winding 1	Pin 1
black	Motor winding 2	Pin 2
white	Motor winding 3	Pin 3
	N.C.	Pin 4

Connector	**Part number**
Molex	39-01-2040

Connection sensors (Cable AWG 24)

yellow	Hall sensor 1*	Pin 1
brown	Hall sensor 2*	Pin 2
grey	Hall sensor 3*	Pin 3
blue	GND	Pin 4
green	V_{Hall} 4.5...24 VDC	Pin 5
	N.C.	Pin 6

Connector	**Part number**
Molex	43025-0600

Wiring diagram for Hall sensors see p. 59
*Internal pull-up (7...13 kΩ) on pin 5

Connection NTC (Cable AWG 24)

pink	NTC
blue	NTC

Resistance 25°C: 5 kΩ ±1%, beta (25–85°C): 3490K

Operating Range

Comments

🟥 Continuous operation
▨ Continuous operation with reduced thermal resistance R_{th2} 50%
☐ Intermittent operation
— **Assigned power rating**

maxon Modular System Details on catalog page 46

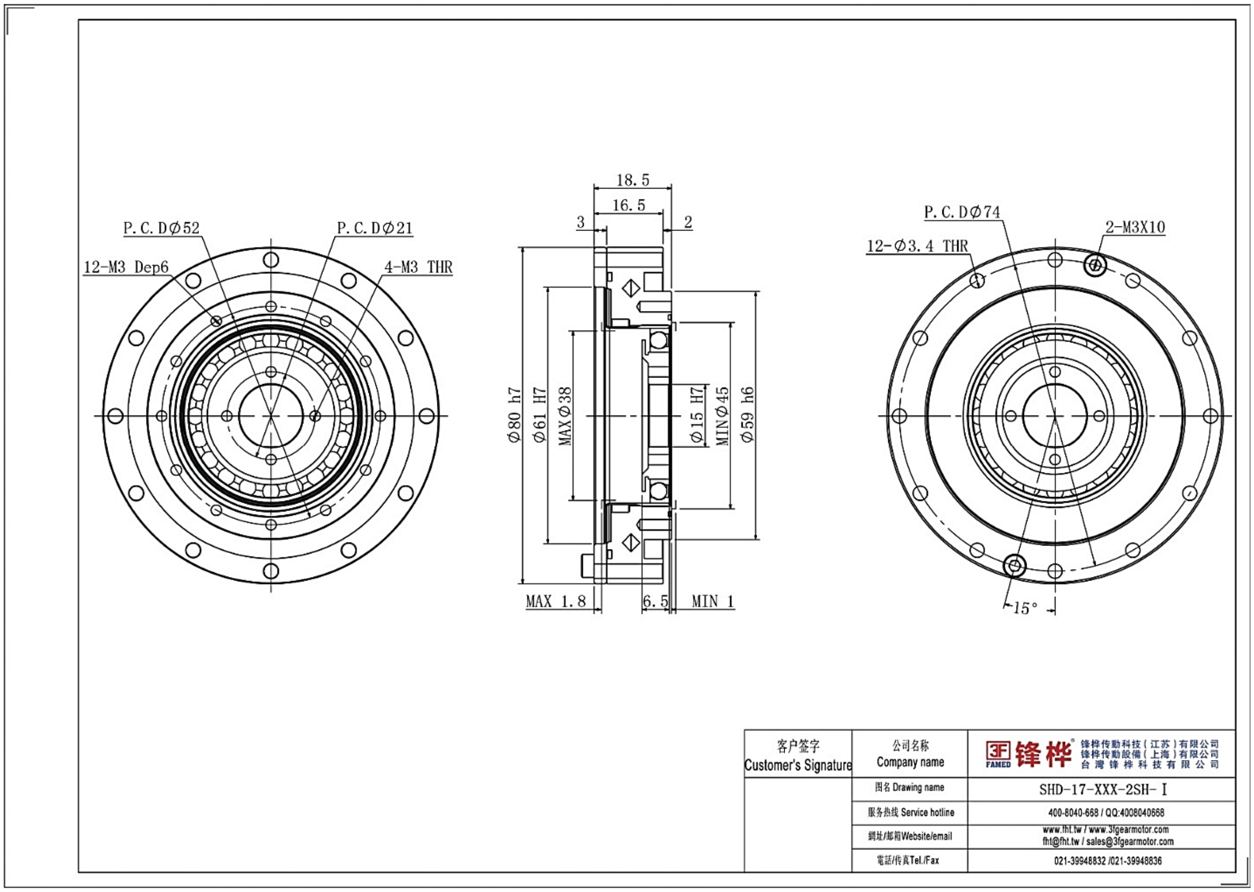
Recommended Electronics:	
Notes	Page **46**
ESCON 36/3 EC	501
ESCON Mod. 50/4 EC-S	501
ESCON Module 50/5	501
ESCON 50/5	503
DEC Module 50/5	505
EPOS4 Micro 24/5	509
EPOS4 Mod./Comp. 50/5	510
EPOS4 Comp. 24/5 3-axes	511
EPOS4 50/5	515
EPOS4 Disk 60/12	517
EPOS2 P 24/5	520

February 2021 edition / subject to change

maxon EC motor 317

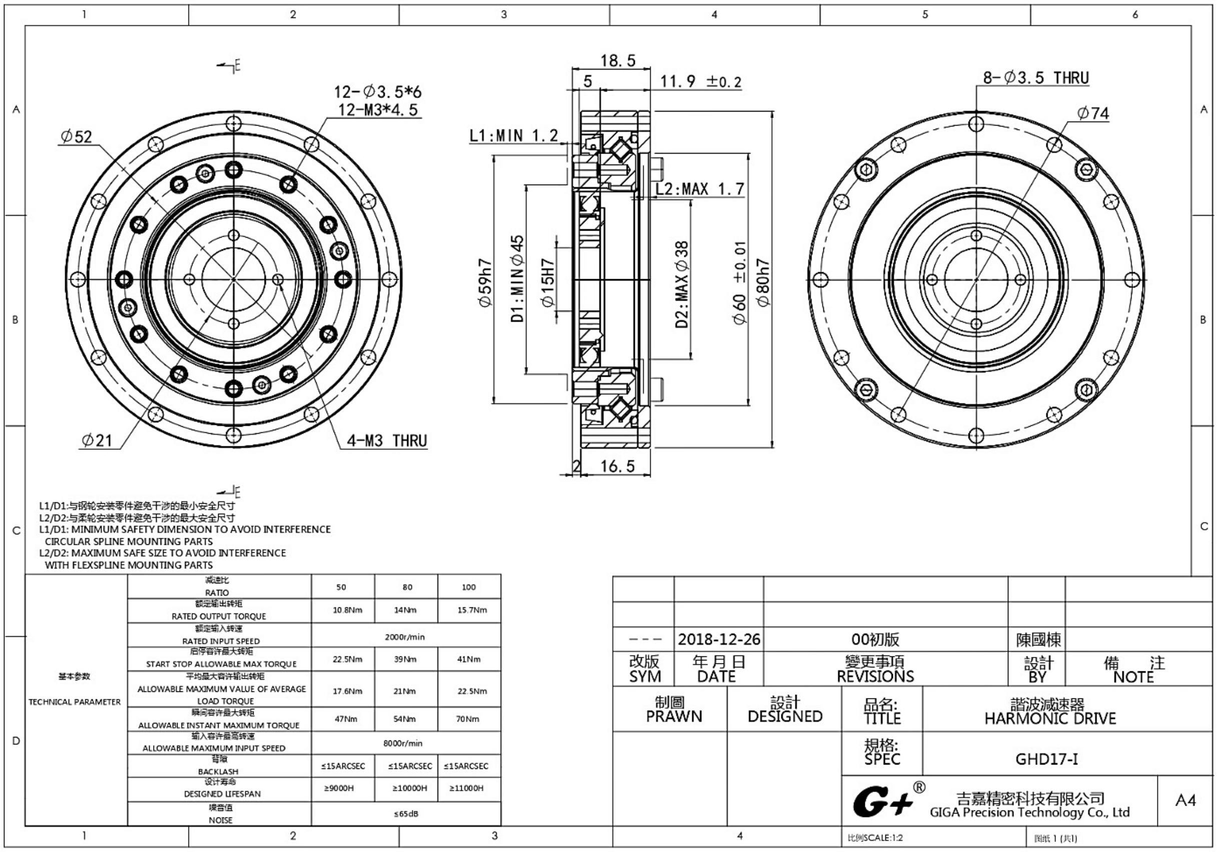
Reproduce from [81].

Appendix C Harmonic Drive SHD-17 by 3F Famed



Reproduced from [85].

Appendix D Harmonic Drive GHD-17 by Giga Precision Technology Co., Ltd



L1/D1:与钢轮安装零件避免干涉的最小安全尺寸
L2/D2:与柔轮安装零件避免干涉的最大安全尺寸
L1/D1: MINIMUM SAFETY DIMENSION TO AVOID INTERFERENCE
CIRCULAR SPLINE MOUNTING PARTS
L2/D2: MAXIMUM SAFE SIZE TO AVOID INTERFERENCE
WITH FLEXSPLINE MOUNTING PARTS

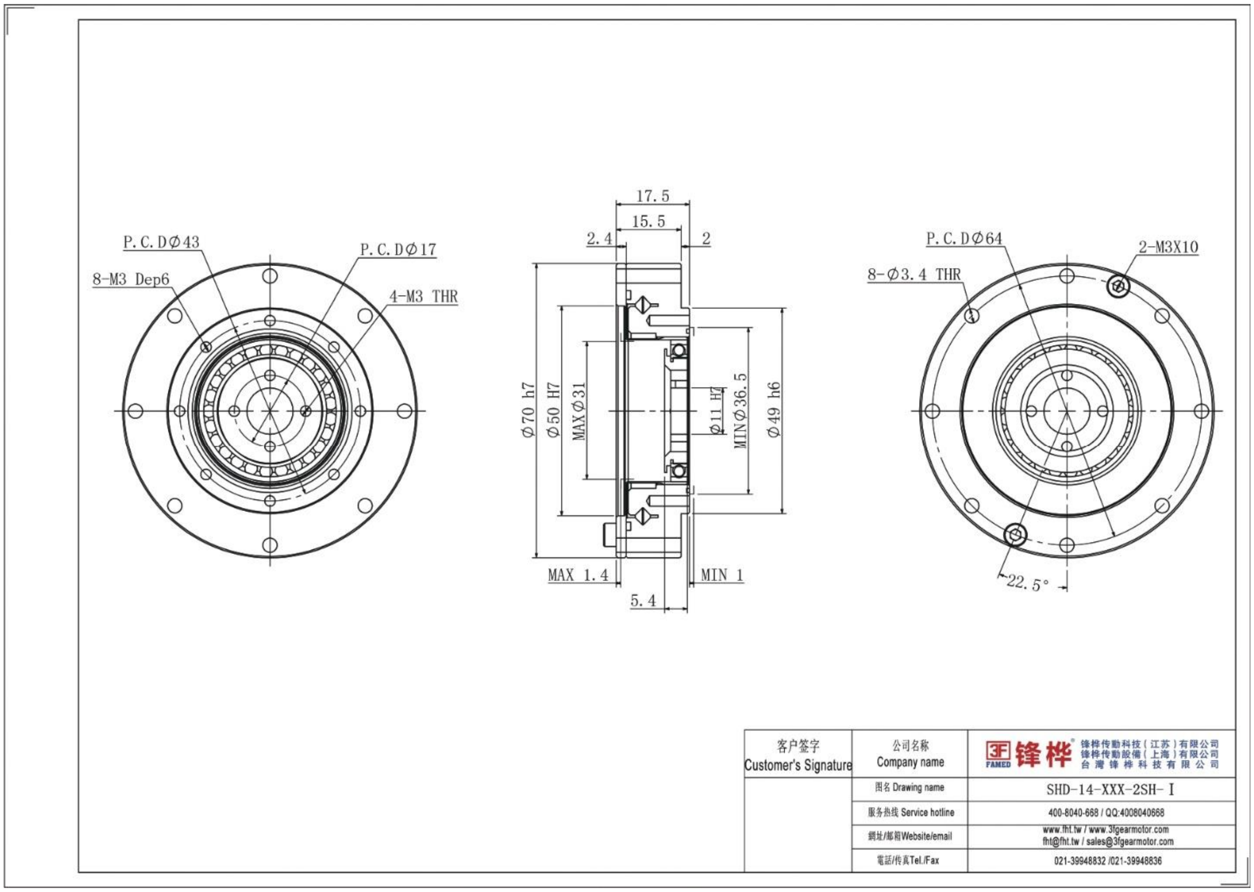
基本参数 TECHNICAL PARAMETER	减速比 RATIO	50	80	100
	额定输出转矩 RATED OUTPUT TORQUE	10.8Nm	14Nm	15.7Nm
	额定输入转速 RATED INPUT SPEED	2000r/min		
	启停容许最大转矩 START STOP ALLOWABLE MAX TORQUE	22.5Nm	39Nm	41Nm
	平均最大容许输出转矩 ALLOWABLE MAXIMUM VALUE OF AVERAGE LOAD TORQUE	17.6Nm	21Nm	22.5Nm
	瞬间容许最大转矩 ALLOWABLE INSTANT MAXIMUM TORQUE	47Nm	54Nm	70Nm
	输入容许最高转速 ALLOWABLE MAXIMUM INPUT SPEED	8000r/min		
	背隙 BACKLASH	≤15ARCSEC	≤15ARCSEC	≤15ARCSEC
	设计寿命 DESIGNED LIFESPAN	≥9000H	≥10000H	≥11000H
	噪音值 NOISE	≤65dB		

---	2018-12-26	00初版	陳國棟	
改版 SYM	年月日 DATE	變更事項 REVISIONS	設計 BY	備 注 NOTE

制圖 PRAWN	設計 DESIGNED	品名: TITLE	諧波減速器 HARMONIC DRIVE
		規格: SPEC	GHD17-I
		吉嘉精密科技有限公司 GIGA Precision Technology Co., Ltd	A4
		比例SCALE:1:2	图纸 1 (共1)

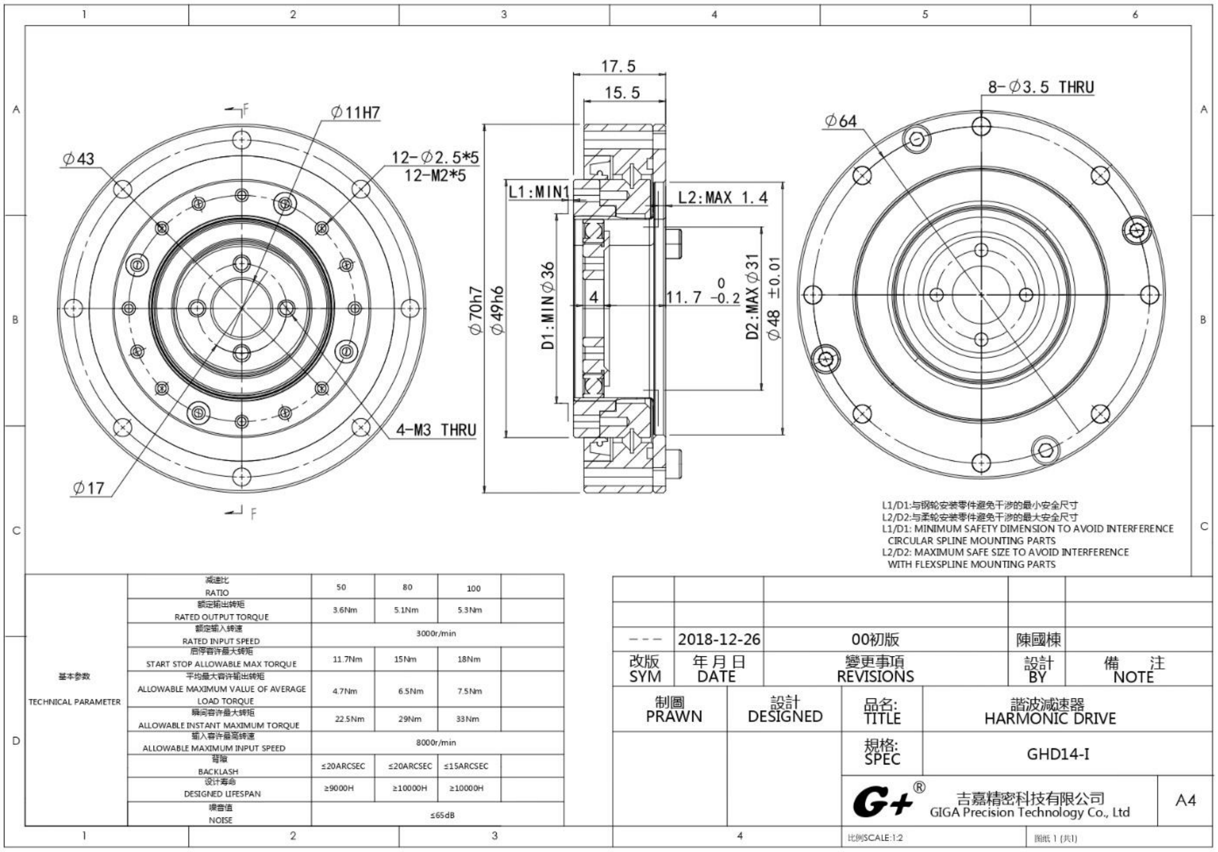
Reproduced from [86].

Appendix E Harmonic Drive SHD-14 by 3F Famed



Reproduced from [85].

Appendix F Harmonic Drive GHD-14 by Giga Precision Technology Co., Ltd



L1/D1:与钢轮安装零件避免干涉的最小安全尺寸
L2/D2:与柔轮安装零件避免干涉的最大安全尺寸
L1/D1: MINIMUM SAFETY DIMENSION TO AVOID INTERFERENCE CIRCULAR SPLINE MOUNTING PARTS
L2/D2: MAXIMUM SAFE SIZE TO AVOID INTERFERENCE WITH FLEXSPLINE MOUNTING PARTS

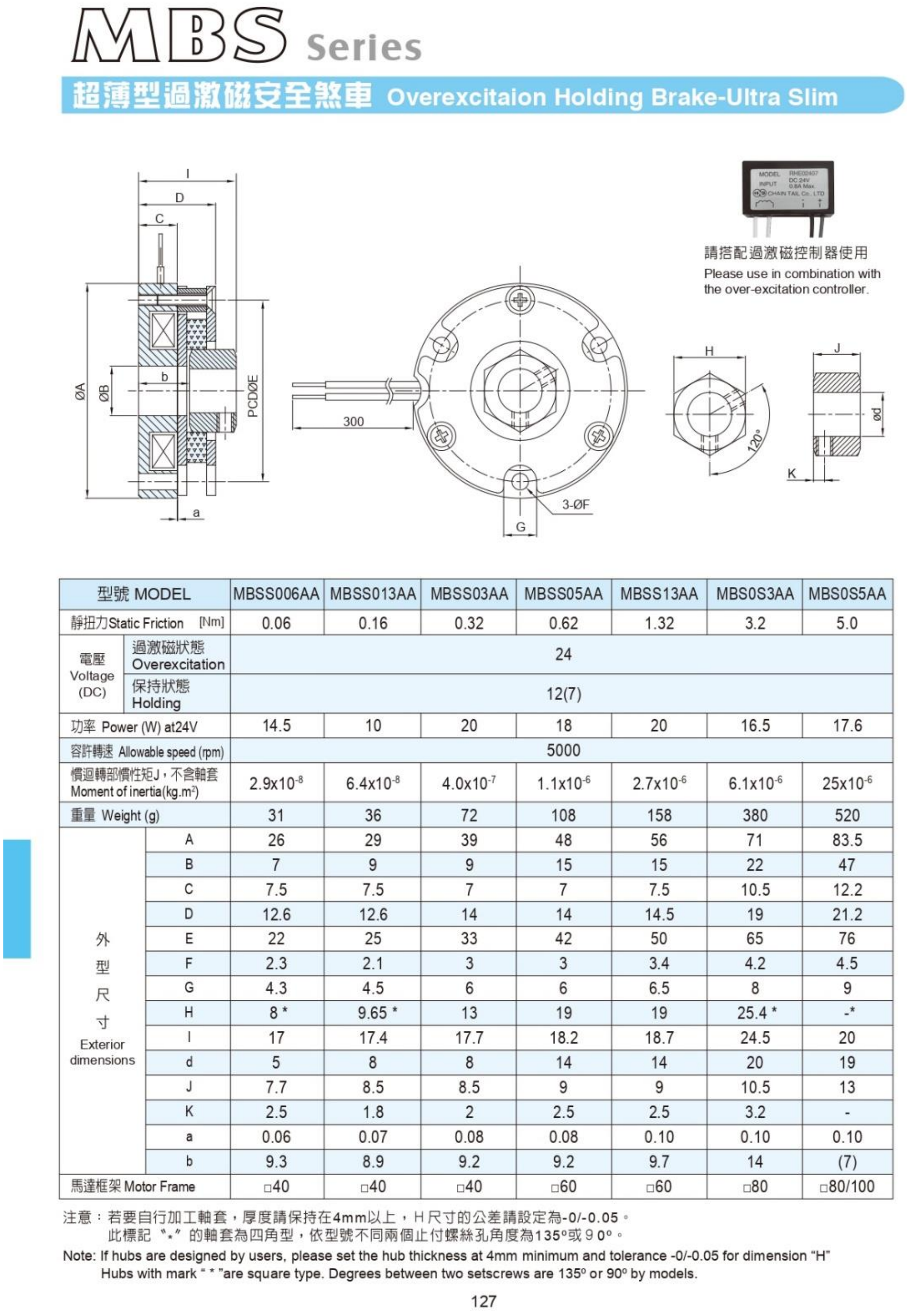
基本参数 TECHNICAL PARAMETER	减速比 RATIO	50	80	100	
	额定输出转矩 RATED OUTPUT TORQUE	3.6Nm	5.1Nm	5.3Nm	
	额定输入转速 RATED INPUT SPEED	3000r/min			
	启停容许最大转矩 START STOP ALLOWABLE MAX TORQUE	11.7Nm	15Nm	18Nm	
	平均最大容许输出转矩 ALLOWABLE MAXIMUM VALUE OF AVERAGE LOAD TORQUE	4.7Nm	6.5Nm	7.5Nm	
	瞬间容许最大转矩 ALLOWABLE INSTANT MAXIMUM TORQUE	22.5Nm	29Nm	33Nm	
	输入容许最高转速 ALLOWABLE MAXIMUM INPUT SPEED	8000r/min			
	背隙 BACKLASH	≤20ARCSEC	≤20ARCSEC	≤15ARCSEC	
	设计寿命 DESIGNED LIFESPAN	≥9000H	≥10000H	≥10000H	
	噪音值 NOISE	≤65dB			

改版 SYM	年月日 DATE	變更事項 REVISIONS	設計 BY	備 注 NOTE
– – –	2018-12-26	00初版	陳國棟	

制圖 PRAWN
設計 DESIGNED
品名: TITLE 諧波減速器 HARMONIC DRIVE
規格: SPEC GHD14-I
G+® 吉嘉精密科技有限公司 GIGA Precision Technology Co., Ltd

Reproduced from [86].

Appendix G Overexcitation Holding Brake-Ultra Slim, MBS Series by Chain Tail Co., Ltd.



MBS Series

超薄型過激磁安全煞車 Overexcitaion Holding Brake-Ultra Slim

請搭配過激磁控制器使用
Please use in combination with the over-excitation controller.

型號 MODEL		MBSS006AA	MBSS013AA	MBSS03AA	MBSS05AA	MBSS13AA	MBS0S3AA	MBS0S5AA
靜扭力Static Friction [Nm]		0.06	0.16	0.32	0.62	1.32	3.2	5.0
電壓 Voltage (DC)	過激磁狀態 Overexcitation	24						
	保持狀態 Holding	12(7)						
功率 Power (W) at24V		14.5	10	20	18	20	16.5	17.6
容許轉速 Allowable speed (rpm)		5000						
慣迴轉部慣性矩J，不含軸套 Moment of inertia(kg.m^2)		$2.9x10^{-8}$	$6.4x10^{-8}$	$4.0x10^{-7}$	$1.1x10^{-6}$	$2.7x10^{-6}$	$6.1x10^{-6}$	$25x10^{-6}$
重量 Weight (g)		31	36	72	108	158	380	520
外型尺寸 Exterior dimensions	A	26	29	39	48	56	71	83.5
	B	7	9	9	15	15	22	47
	C	7.5	7.5	7	7	7.5	10.5	12.2
	D	12.6	12.6	14	14	14.5	19	21.2
	E	22	25	33	42	50	65	76
	F	2.3	2.1	3	3	3.4	4.2	4.5
	G	4.3	4.5	6	6	6.5	8	9
	H	8 *	9.65 *	13	19	19	25.4 *	-*
	I	17	17.4	17.7	18.2	18.7	24.5	20
	d	5	8	8	14	14	20	19
	J	7.7	8.5	8.5	9	9	10.5	13
	K	2.5	1.8	2	2.5	2.5	3.2	-
	a	0.06	0.07	0.08	0.08	0.10	0.10	0.10
	b	9.3	8.9	9.2	9.2	9.7	14	(7)
馬達框架 Motor Frame		□40	□40	□40	□60	□60	□80	□80/100

注意：若要自行加工軸套，厚度請保持在4mm以上，H尺寸的公差請設定為-0/-0.05。
此標記〝*〞的軸套為四角型，依型號不同兩個止付螺絲孔角度為135°或90°。

Note: If hubs are designed by users, please set the hub thickness at 4mm minimum and tolerance -0/-0.05 for dimension "H"
Hubs with mark " * "are square type. Degrees between two setscrews are 135° or 90° by models.

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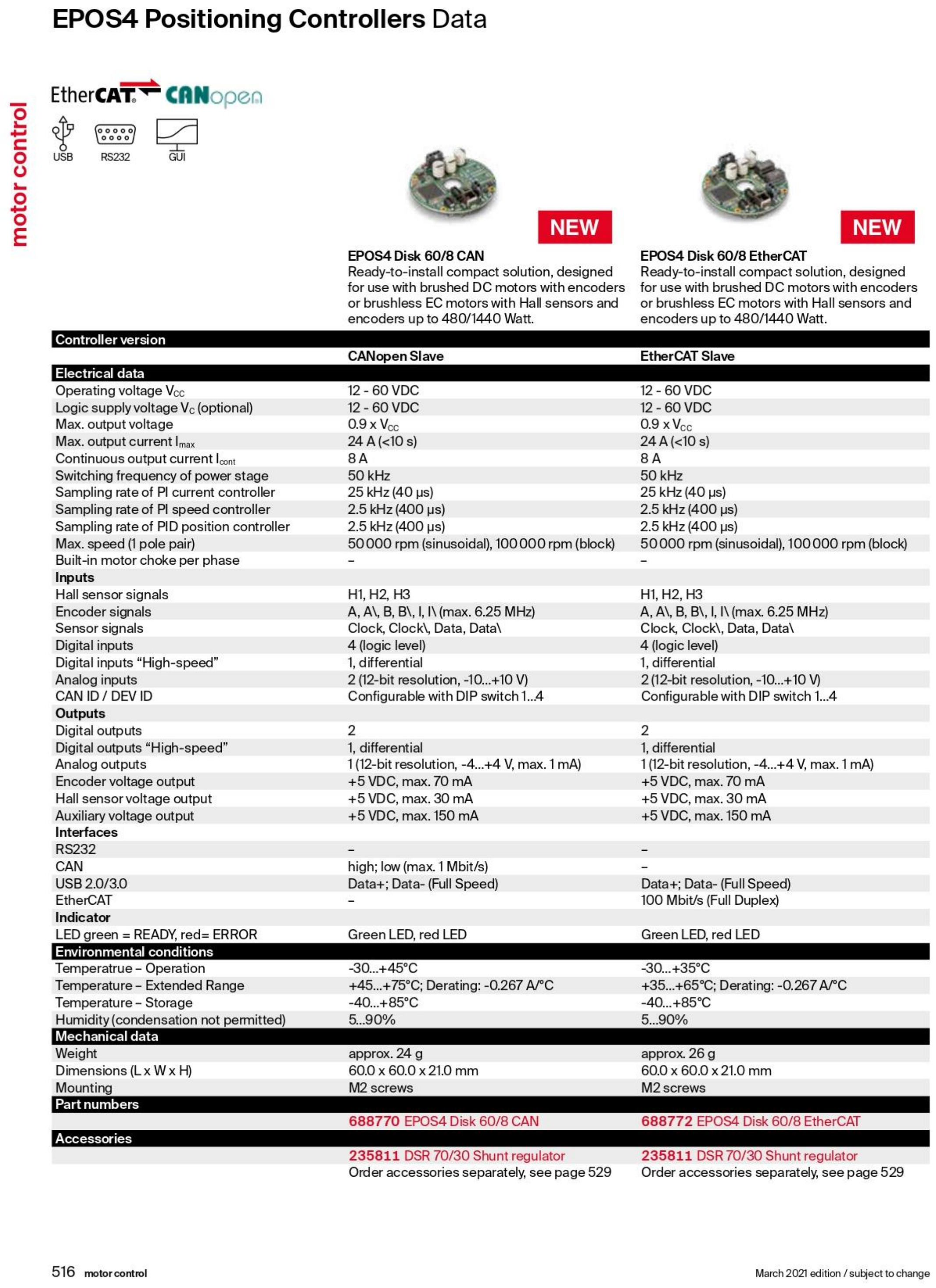
Reproduced from [87].

Appendix H EPOS4 Maxon Positioning Controller Data.



EPOS4 Positioning Controllers Data

motor control

EtherCAT CANopen

USB RS232 GUI

NEW NEW

EPOS4 Disk 60/8 CAN
Ready-to-install compact solution, designed for use with brushed DC motors with encoders or brushless EC motors with Hall sensors and encoders up to 480/1440 Watt.

EPOS4 Disk 60/8 EtherCAT
Ready-to-install compact solution, designed for use with brushed DC motors with encoders or brushless EC motors with Hall sensors and encoders up to 480/1440 Watt.

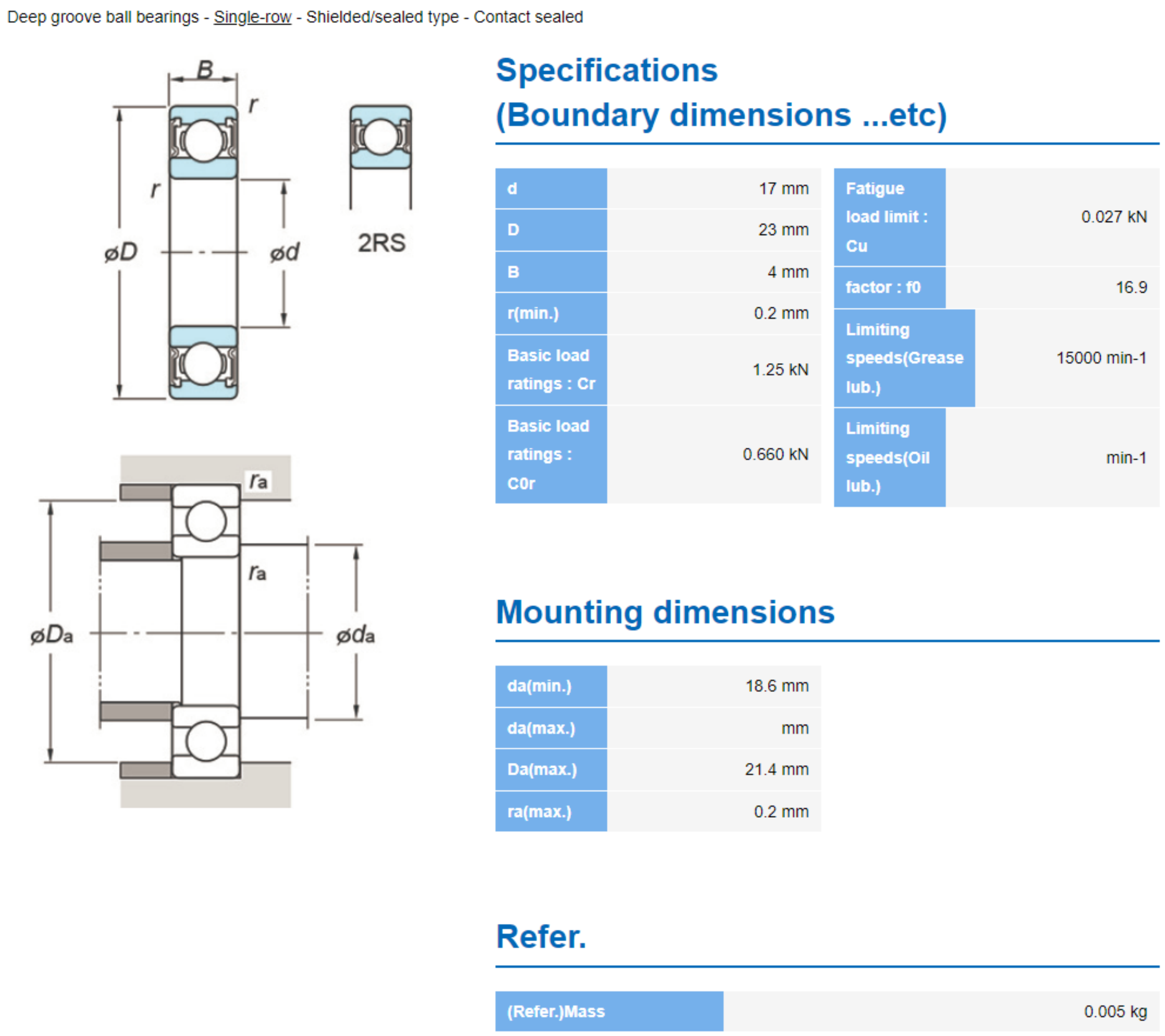
	EPOS4 Disk 60/8 CAN	EPOS4 Disk 60/8 EtherCAT
Controller version		
	CANopen Slave	**EtherCAT Slave**
Electrical data		
Operating voltage V_{CC}	12 - 60 VDC	12 - 60 VDC
Logic supply voltage V_C (optional)	12 - 60 VDC	12 - 60 VDC
Max. output voltage	0.9 x V_{CC}	0.9 x V_{CC}
Max. output current I_{max}	24 A (<10 s)	24 A (<10 s)
Continuous output current I_{cont}	8 A	8 A
Switching frequency of power stage	50 kHz	50 kHz
Sampling rate of PI current controller	25 kHz (40 µs)	25 kHz (40 µs)
Sampling rate of PI speed controller	2.5 kHz (400 µs)	2.5 kHz (400 µs)
Sampling rate of PID position controller	2.5 kHz (400 µs)	2.5 kHz (400 µs)
Max. speed (1 pole pair)	50 000 rpm (sinusoidal), 100 000 rpm (block)	50 000 rpm (sinusoidal), 100 000 rpm (block)
Built-in motor choke per phase	–	–
Inputs		
Hall sensor signals	H1, H2, H3	H1, H2, H3
Encoder signals	A, A\, B, B\, I, I\ (max. 6.25 MHz)	A, A\, B, B\, I, I\ (max. 6.25 MHz)
Sensor signals	Clock, Clock\, Data, Data\	Clock, Clock\, Data, Data\
Digital inputs	4 (logic level)	4 (logic level)
Digital inputs "High-speed"	1, differential	1, differential
Analog inputs	2 (12-bit resolution, -10…+10 V)	2 (12-bit resolution, -10…+10 V)
CAN ID / DEV ID	Configurable with DIP switch 1…4	Configurable with DIP switch 1…4
Outputs		
Digital outputs	2	2
Digital outputs "High-speed"	1, differential	1, differential
Analog outputs	1 (12-bit resolution, -4…+4 V, max. 1 mA)	1 (12-bit resolution, -4…+4 V, max. 1 mA)
Encoder voltage output	+5 VDC, max. 70 mA	+5 VDC, max. 70 mA
Hall sensor voltage output	+5 VDC, max. 30 mA	+5 VDC, max. 30 mA
Auxiliary voltage output	+5 VDC, max. 150 mA	+5 VDC, max. 150 mA
Interfaces		
RS232	–	–
CAN	high; low (max. 1 Mbit/s)	–
USB 2.0/3.0	Data+; Data- (Full Speed)	Data+; Data- (Full Speed)
EtherCAT	–	100 Mbit/s (Full Duplex)
Indicator		
LED green = READY, red= ERROR	Green LED, red LED	Green LED, red LED
Environmental conditions		
Temperatrue – Operation	-30…+45°C	-30…+35°C
Temperature – Extended Range	+45…+75°C; Derating: -0.267 A/°C	+35…+65°C; Derating: -0.267 A/°C
Temperature – Storage	-40…+85°C	-40…+85°C
Humidity (condensation not permitted)	5…90%	5…90%
Mechanical data		
Weight	approx. 24 g	approx. 26 g
Dimensions (L x W x H)	60.0 x 60.0 x 21.0 mm	60.0 x 60.0 x 21.0 mm
Mounting	M2 screws	M2 screws
Part numbers		
	688770 EPOS4 Disk 60/8 CAN	**688772** EPOS4 Disk 60/8 EtherCAT
Accessories		
	235811 DSR 70/30 Shunt regulator	**235811** DSR 70/30 Shunt regulator
	Order accessories separately, see page 529	Order accessories separately, see page 529

516 **motor control**

March 2021 edition / subject to change

Reproduced from [83].

Appendix I 6703 2RS: Deep groove ball bearings - Single-row - Shielded/sealed type - Contact sealed



Deep groove ball bearings - Single-row - Shielded/sealed type - Contact sealed

Specifications (Boundary dimensions ...etc)

d	17 mm
D	23 mm
B	4 mm
r(min.)	0.2 mm
Basic load ratings : Cr	1.25 kN
Basic load ratings : C0r	0.660 kN

Fatigue load limit : Cu	0.027 kN
factor : f0	16.9
Limiting speeds(Grease lub.)	15000 min-1
Limiting speeds(Oil lub.)	min-1

Mounting dimensions

da(min.)	18.6 mm
da(max.)	mm
Da(max.)	21.4 mm
ra(max.)	0.2 mm

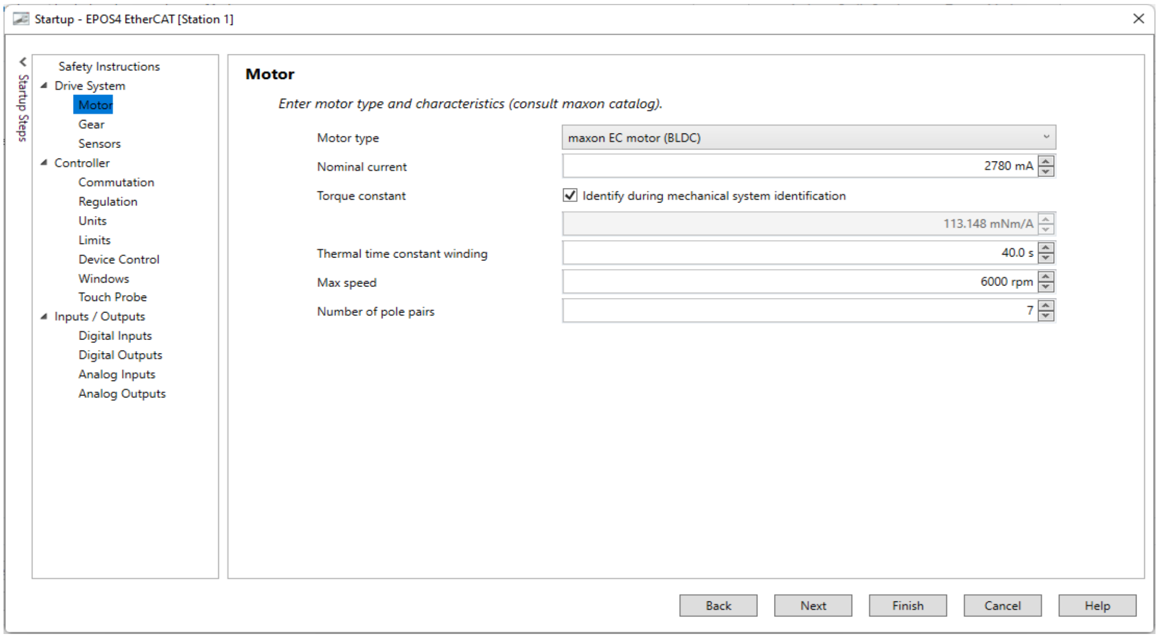
Refer.

(Refer.)Mass	0.005 kg

Reproduced from [88].

Appendix J Specification of Motors in EPOS Studio

The following screenshots from the Maxon EPOS Studio software records all the configurations used during tuning and testing of the maxon EPOS controllers within the integrated actuators.



Motor

Enter motor type and characteristics (consult maxon catalog).

Motor type: maxon EC motor (BLDC)

Nominal current: 2780 mA

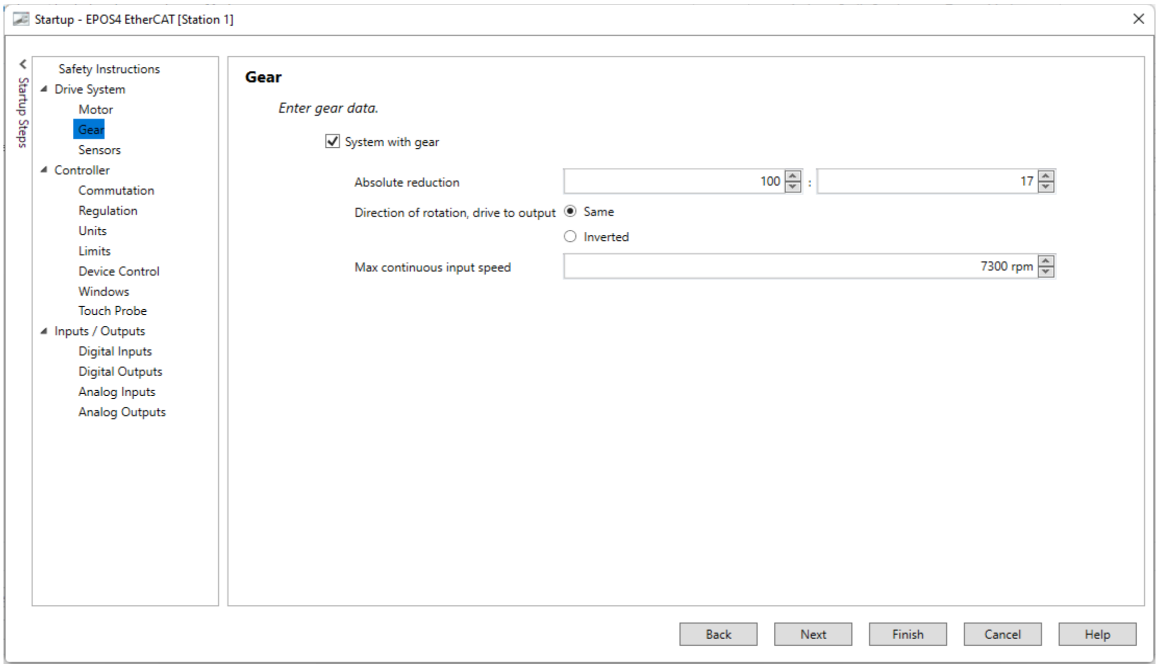
Torque constant: ☑ Identify during mechanical system identification

113.148 mNm/A

Thermal time constant winding: 40.0 s

Max speed: 6000 rpm

Number of pole pairs: 7



Gear

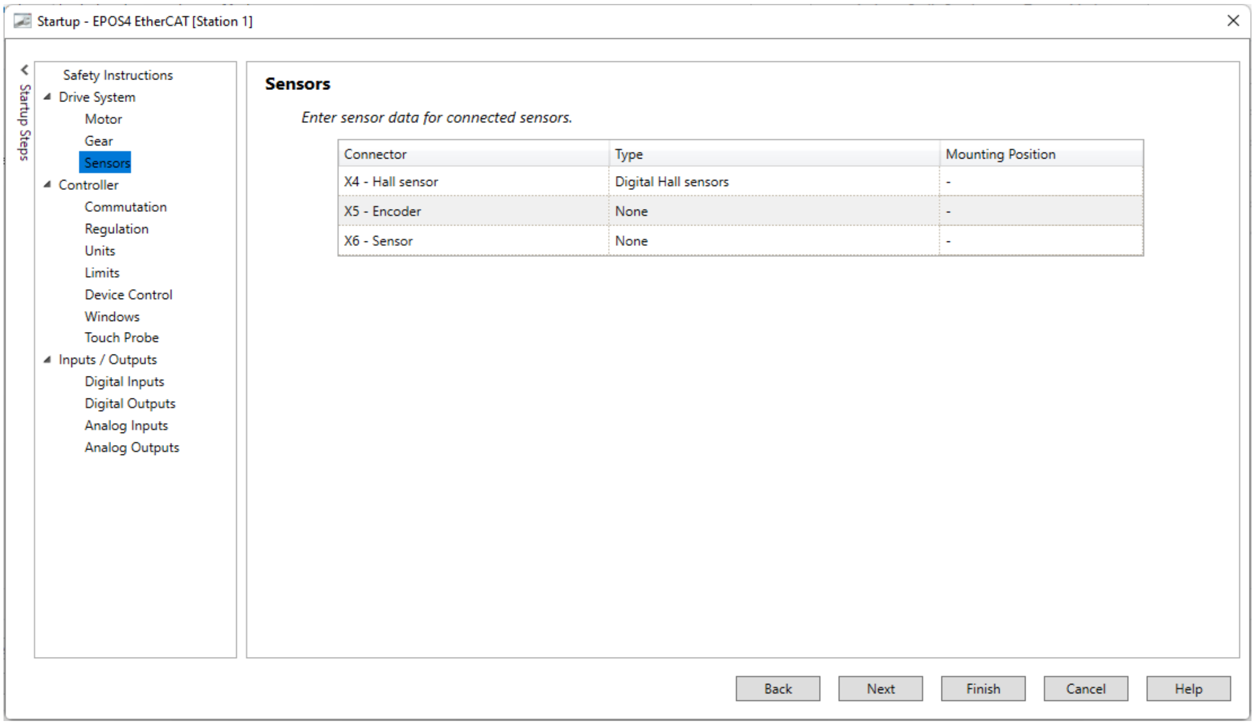
Enter gear data.

☑ System with gear

Absolute reduction: 100 : 17

Direction of rotation, drive to output: ● Same ○ Inverted

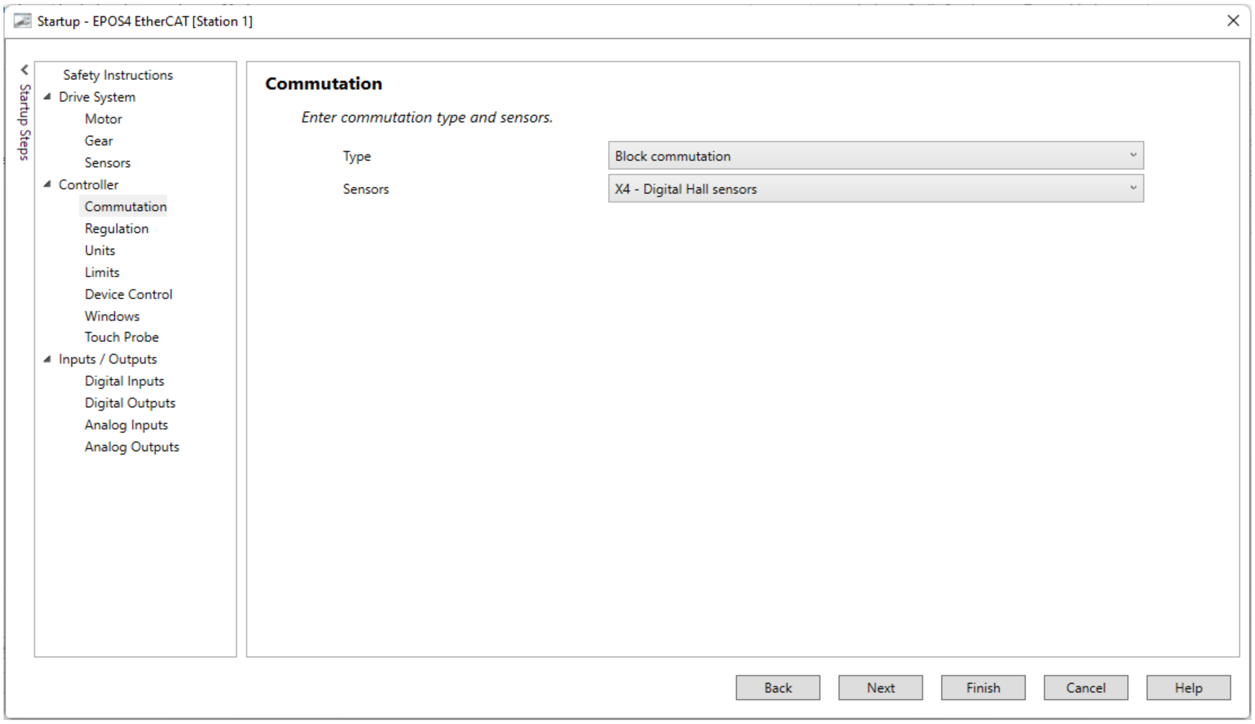
Max continuous input speed: 7300 rpm



Sensors

Enter sensor data for connected sensors.

Connector	Type	Mounting Position
X4 - Hall sensor	Digital Hall sensors	-
X5 - Encoder	None	-
X6 - Sensor	None	-

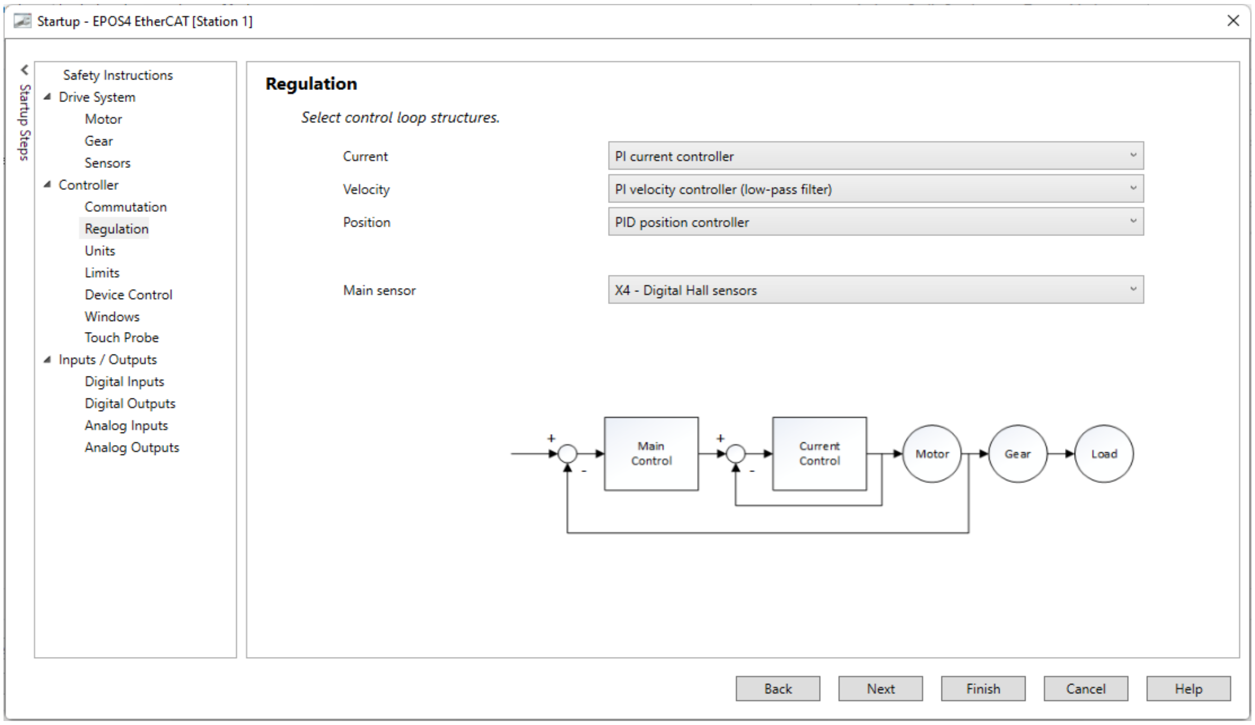


Commutation

Enter commutation type and sensors.

Type: Block commutation

Sensors: X4 - Digital Hall sensors



Regulation

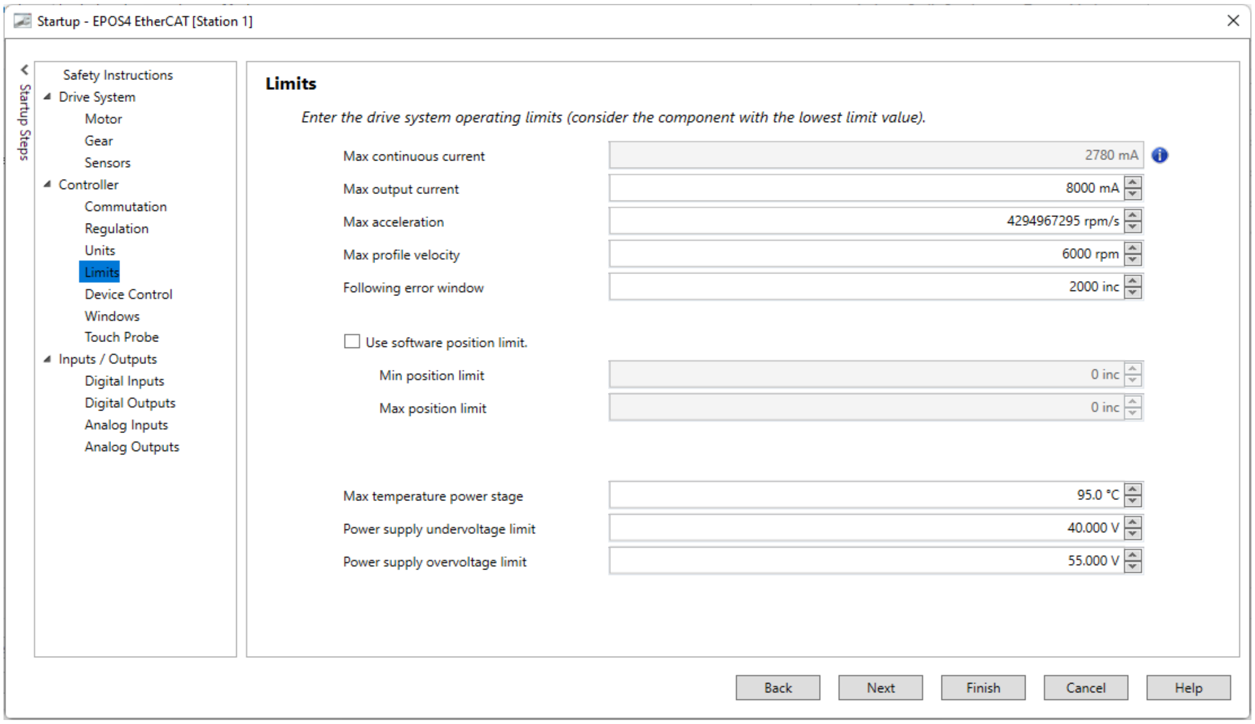
Select control loop structures.

Current: PI current controller

Velocity: PI velocity controller (low-pass filter)

Position: PID position controller

Main sensor: X4 - Digital Hall sensors



Limits

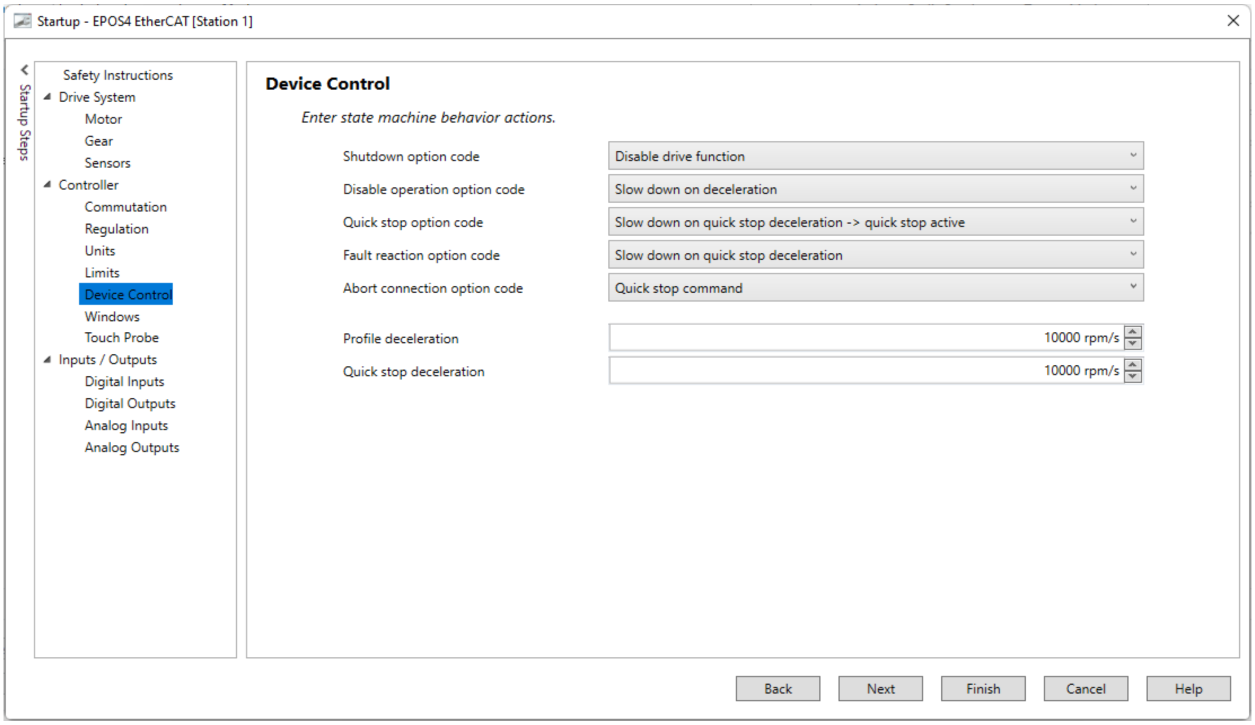
Enter the drive system operating limits (consider the component with the lowest limit value).

Max continuous current	2780 mA
Max output current	8000 mA
Max acceleration	4294967295 rpm/s
Max profile velocity	6000 rpm
Following error window	2000 inc

☐ Use software position limit.

Min position limit	0 inc
Max position limit	0 inc

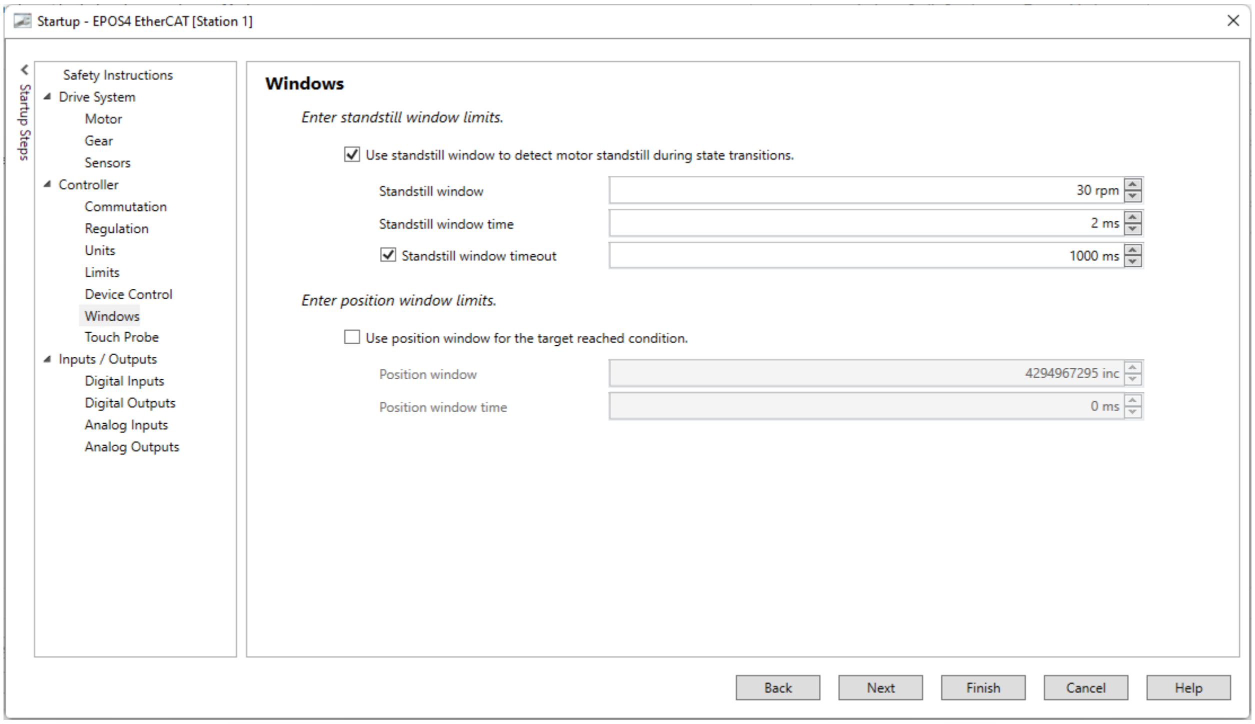
Max temperature power stage	95.0 °C
Power supply undervoltage limit	40.000 V
Power supply overvoltage limit	55.000 V



Device Control

Enter state machine behavior actions.

Shutdown option code	Disable drive function
Disable operation option code	Slow down on deceleration
Quick stop option code	Slow down on quick stop deceleration -> quick stop active
Fault reaction option code	Slow down on quick stop deceleration
Abort connection option code	Quick stop command
Profile deceleration	10000 rpm/s
Quick stop deceleration	10000 rpm/s



Windows

Enter standstill window limits.

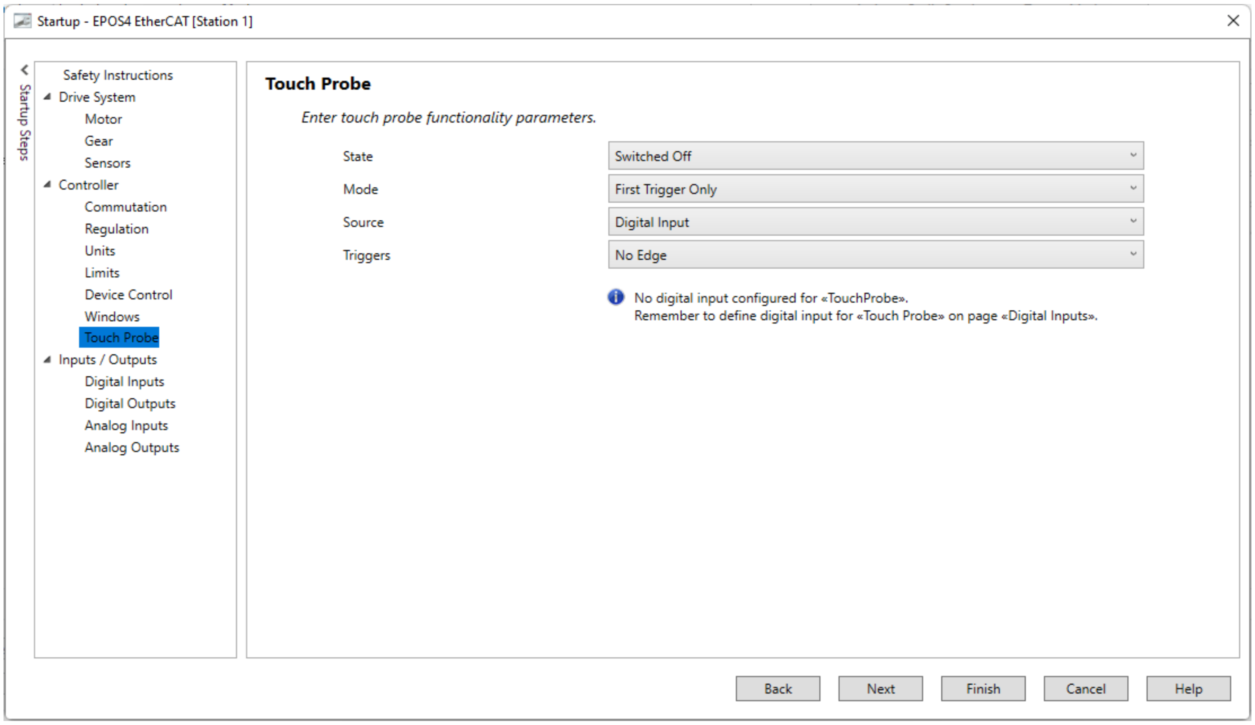
☑ Use standstill window to detect motor standstill during state transitions.

Standstill window	30 rpm
Standstill window time	2 ms
☑ Standstill window timeout	1000 ms

Enter position window limits.

☐ Use position window for the target reached condition.

Position window	4294967295 inc
Position window time	0 ms

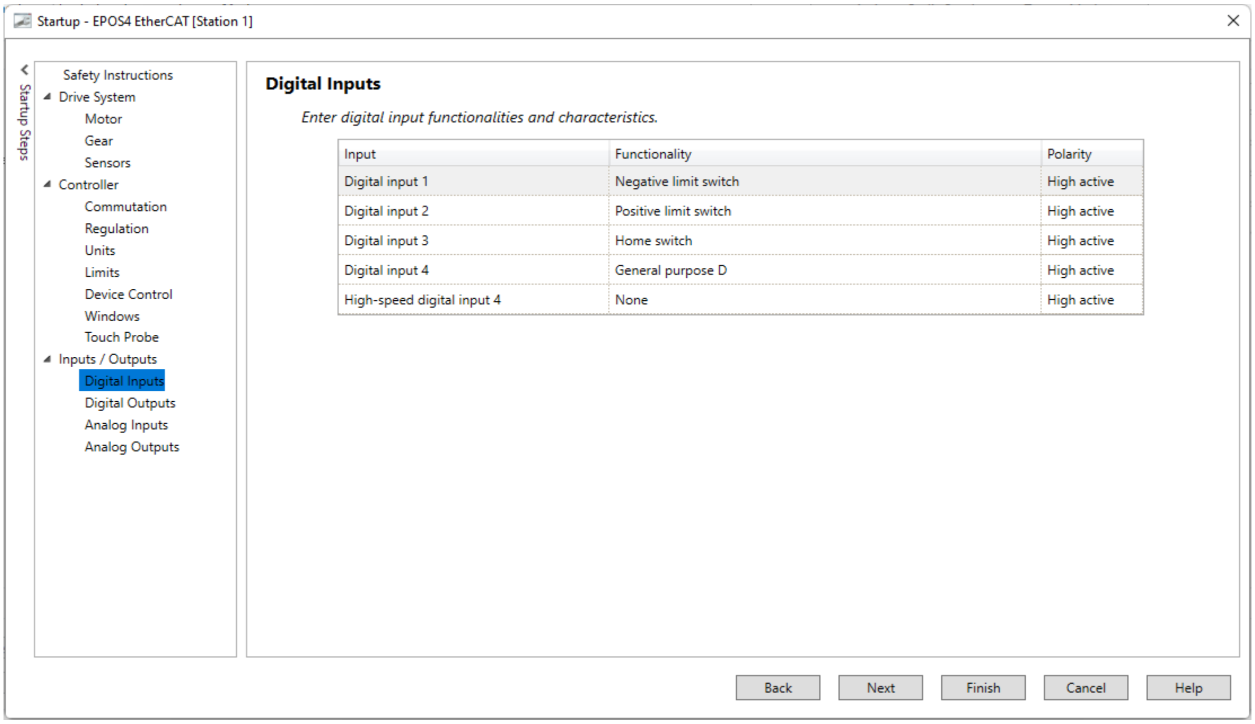


Touch Probe

Enter touch probe functionality parameters.

State	Switched Off
Mode	First Trigger Only
Source	Digital Input
Triggers	No Edge

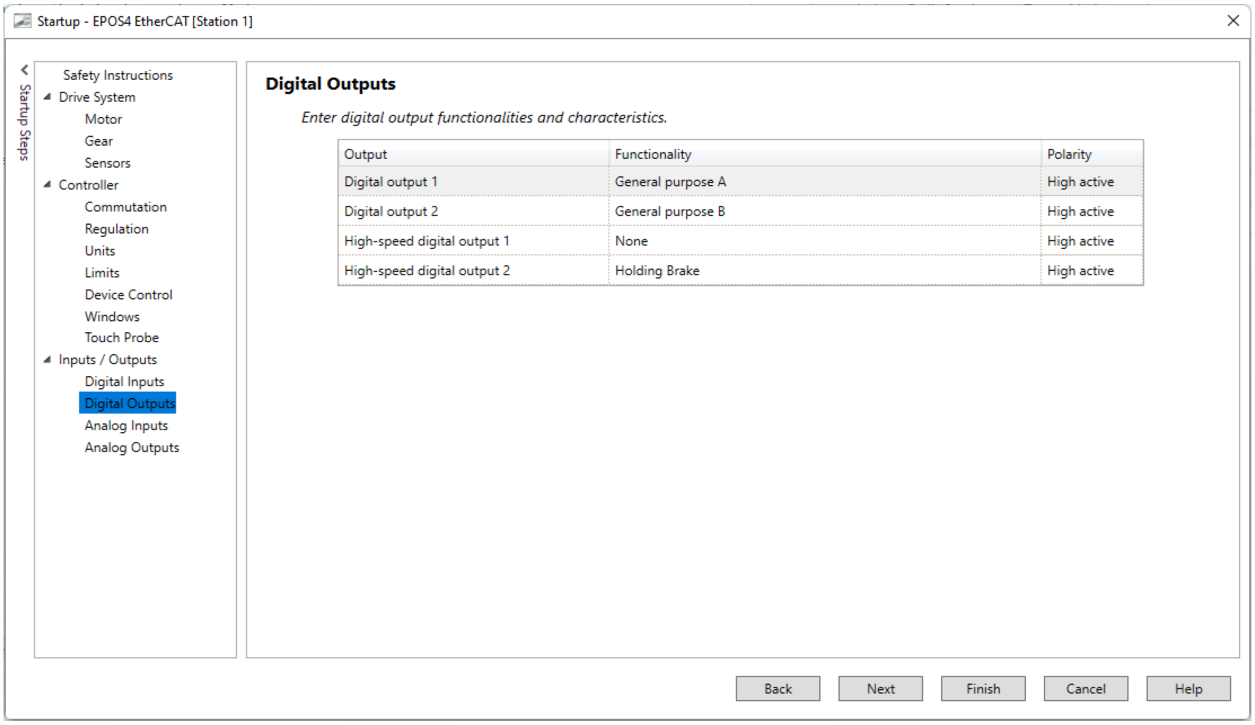
No digital input configured for «TouchProbe».
Remember to define digital input for «Touch Probe» on page «Digital Inputs».



Digital Inputs

Enter digital input functionalities and characteristics.

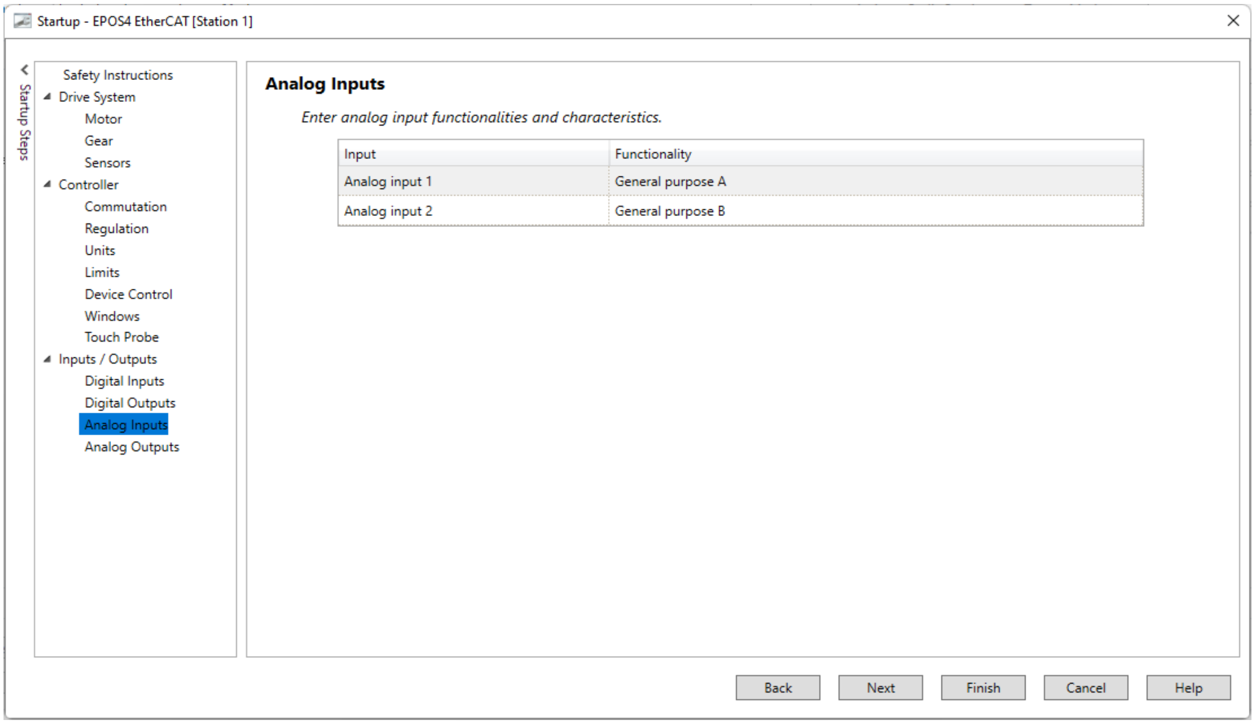
Input	Functionality	Polarity
Digital input 1	Negative limit switch	High active
Digital input 2	Positive limit switch	High active
Digital input 3	Home switch	High active
Digital input 4	General purpose D	High active
High-speed digital input 4	None	High active



Digital Outputs

Enter digital output functionalities and characteristics.

Output	Functionality	Polarity
Digital output 1	General purpose A	High active
Digital output 2	General purpose B	High active
High-speed digital output 1	None	High active
High-speed digital output 2	Holding Brake	High active

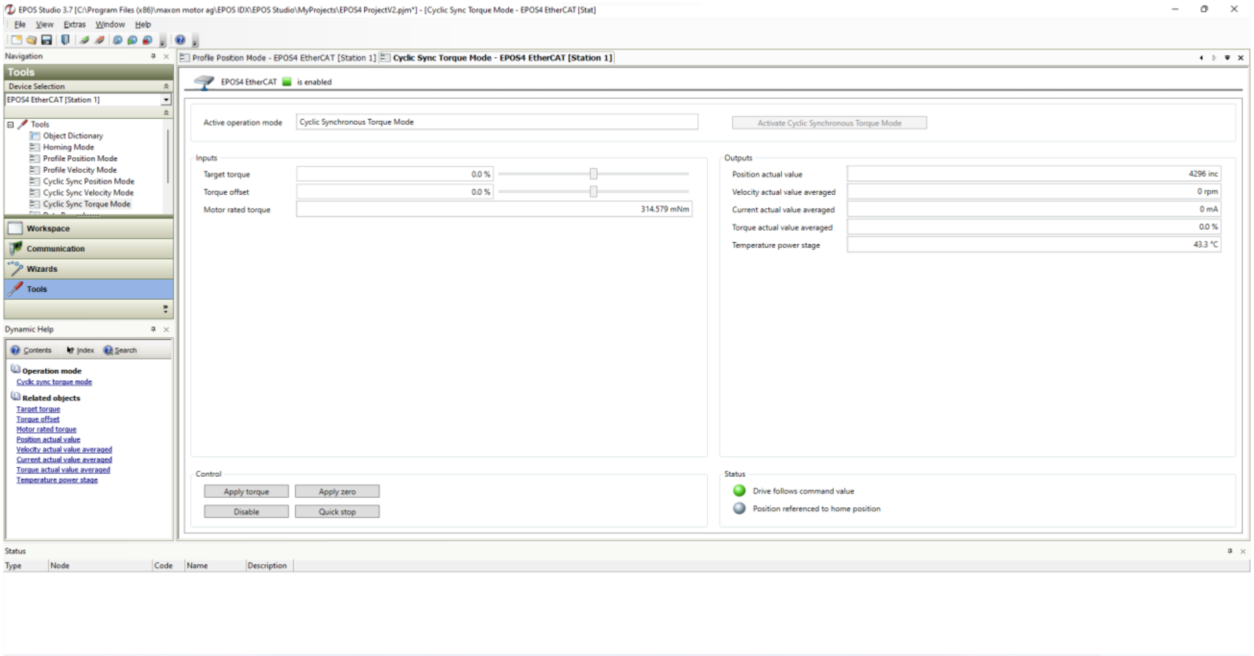


Analog Inputs

Enter analog input functionalities and characteristics.

Input	Functionality
Analog input 1	General purpose A
Analog input 2	General purpose B

Running the motors from EPOS studio after tuning:



EPOS Studio 3.7 [C:\Program Files (x86)\maxon motor ag\EPOS IDX\EPOS Studio\MyProjects\EPOS4 ProjectV2.pjm*] - [Cyclic Sync Torque Mode - EPOS4 EtherCAT [Stat]

Device Selection: EPOS4 EtherCAT [Station 1]

EPOS4 EtherCAT 🟩 is enabled

Active operation mode: Cyclic Synchronous Torque Mode

Inputs

Target torque	0.0 %
Torque offset	0.0 %
Motor rated torque	314.579 mNm

Outputs

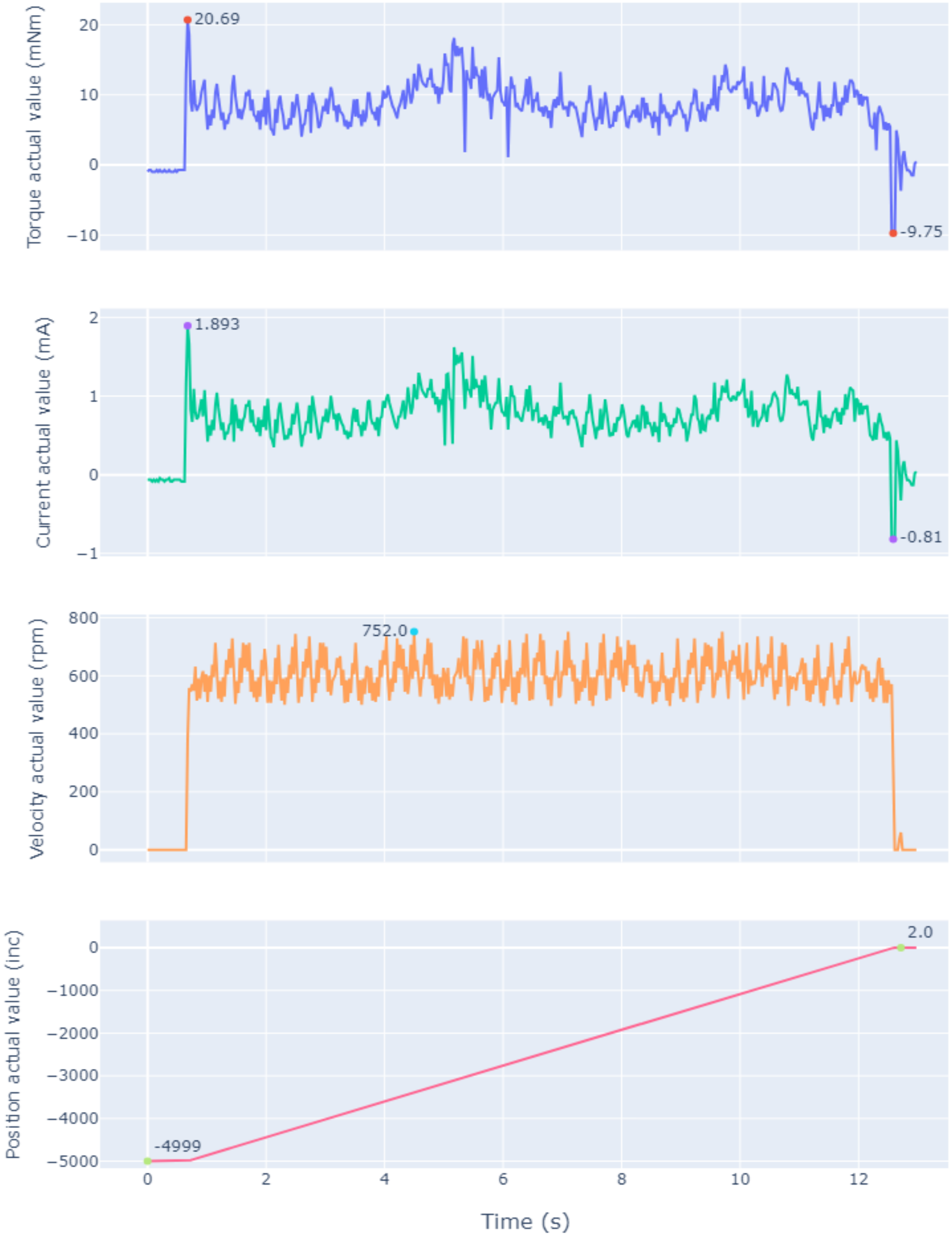
Position actual value	4296 inc
Velocity actual value averaged	0 rpm
Current actual value averaged	0 mA
Torque actual value averaged	0.0 %
Temperature power stage	43.3 °C

Status

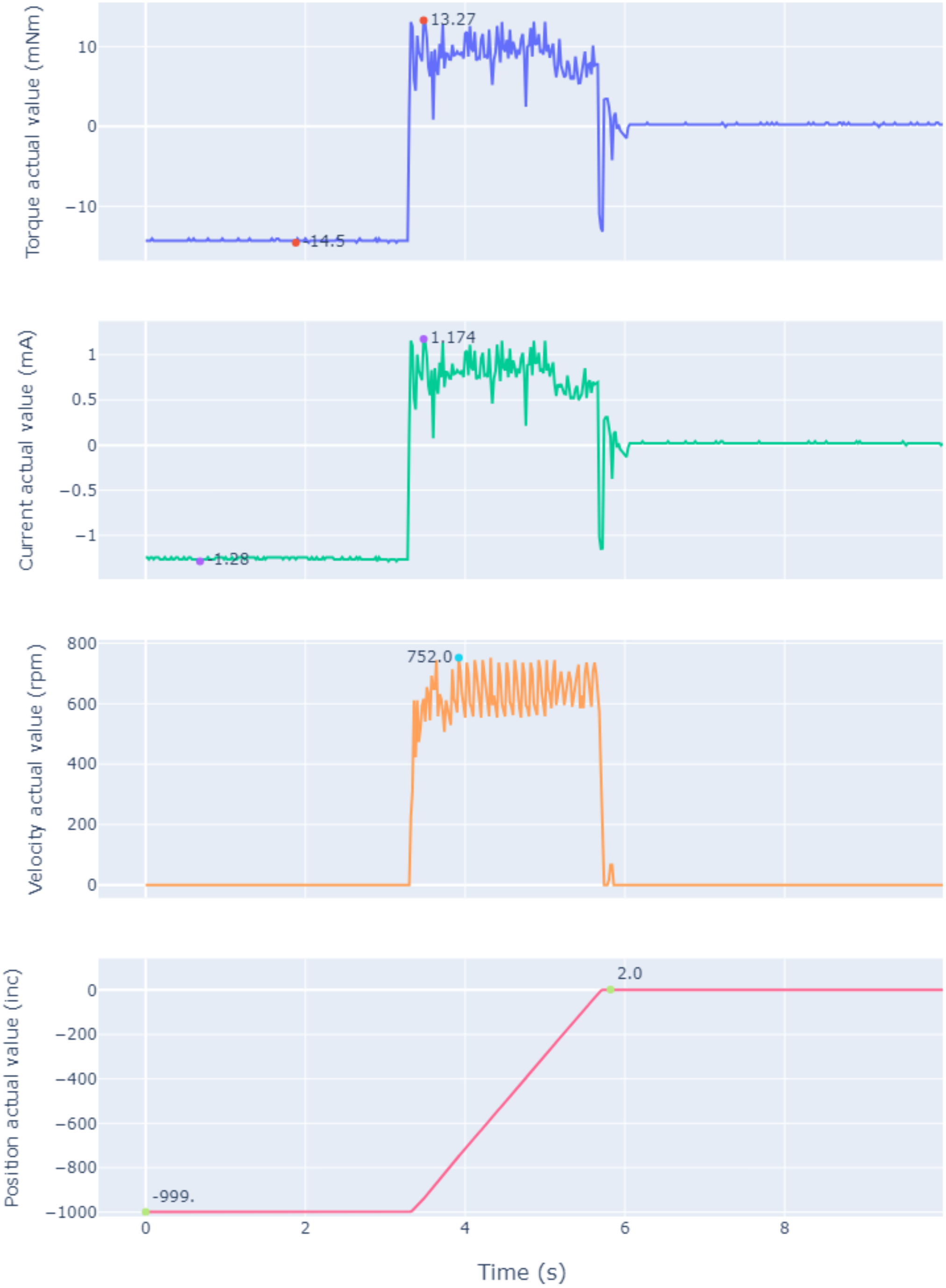
● Drive follows command value

● Position referenced to home position

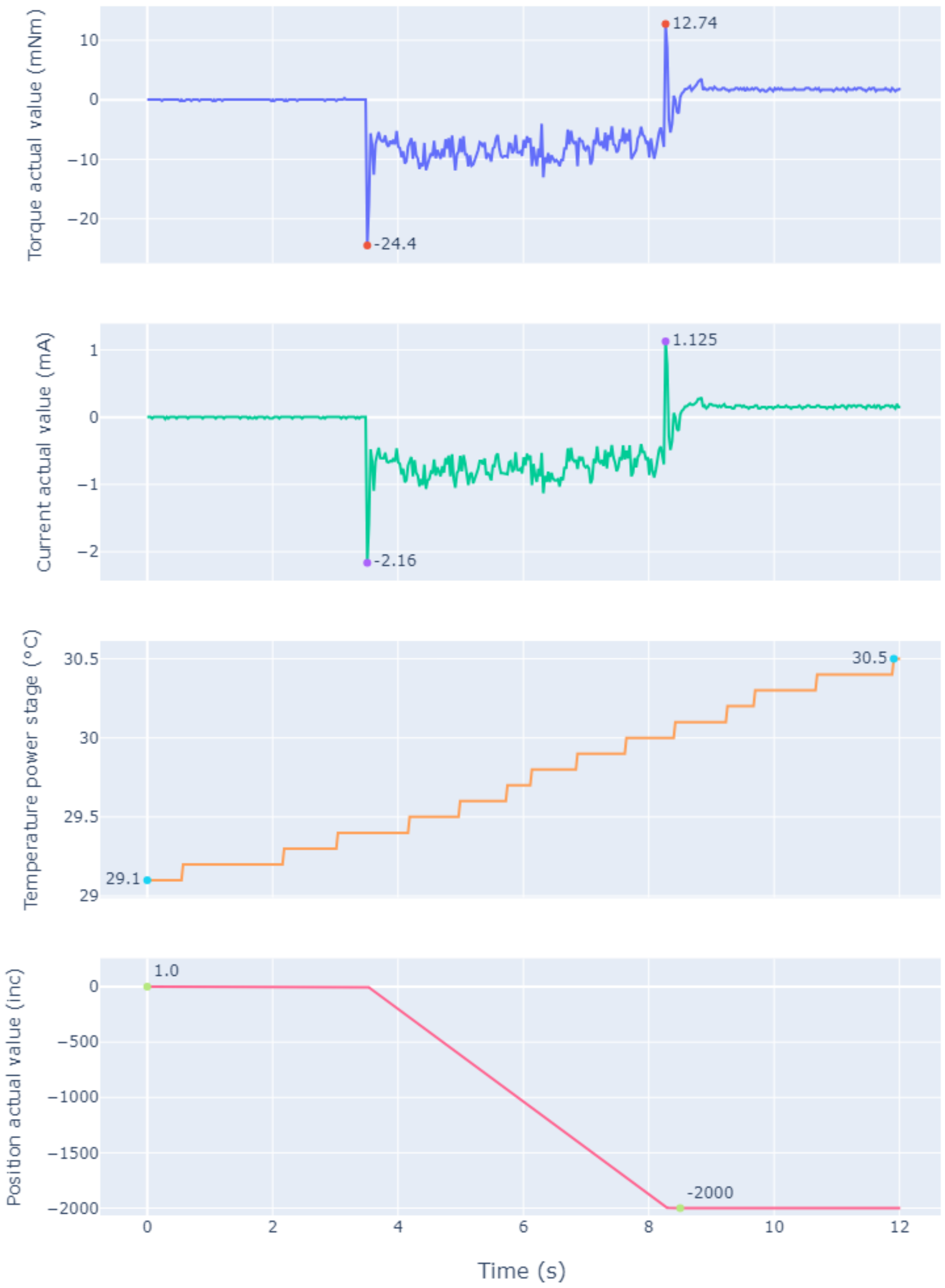
Appendix K Visualization of Motor test data in EPOS Studio



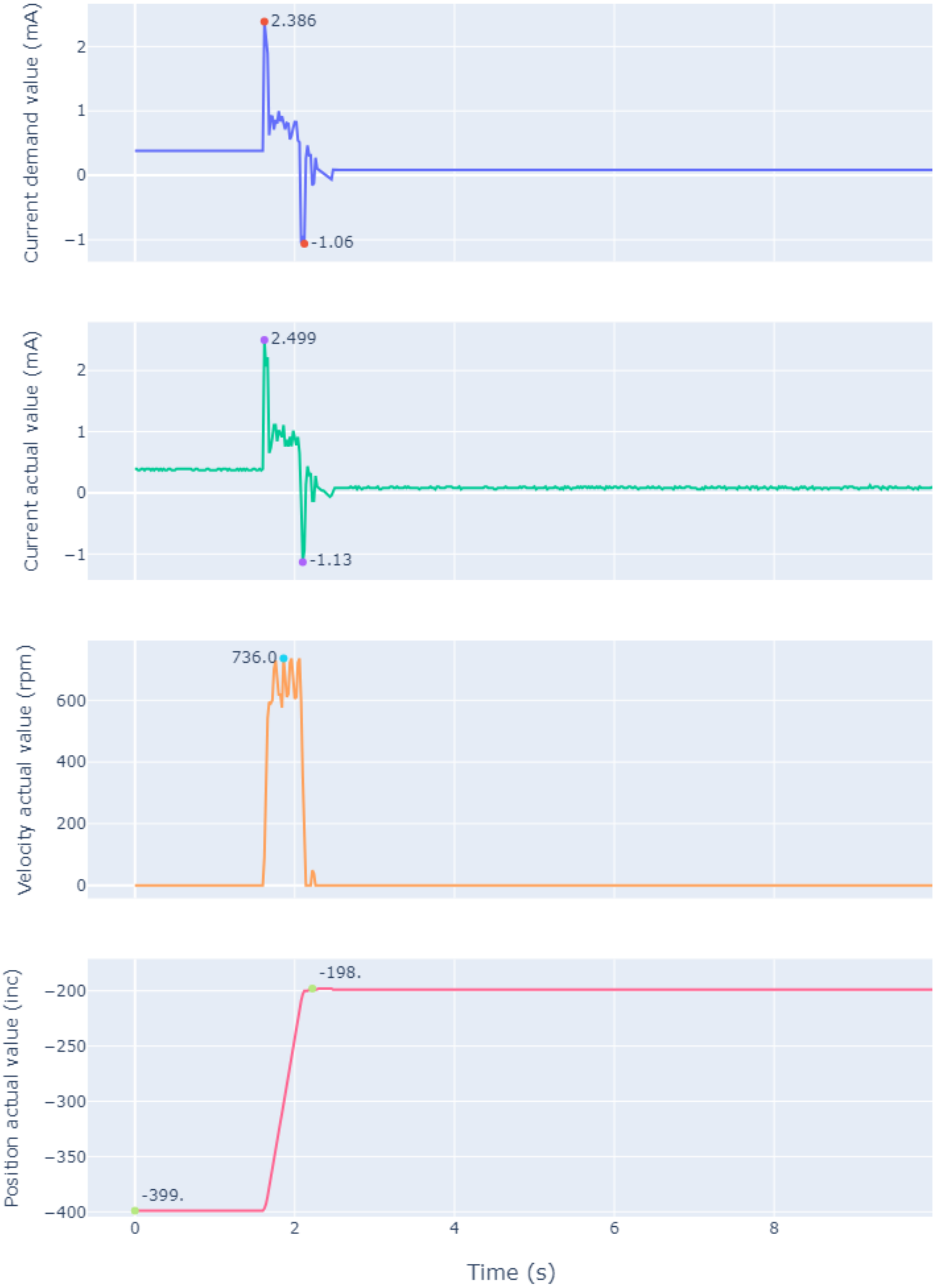
This plot shows the torque, current, velocity, and position for the final version of the EC60 with brakes, going to a specific position with a slow ramp mode under no load in a counter clockwise movement.



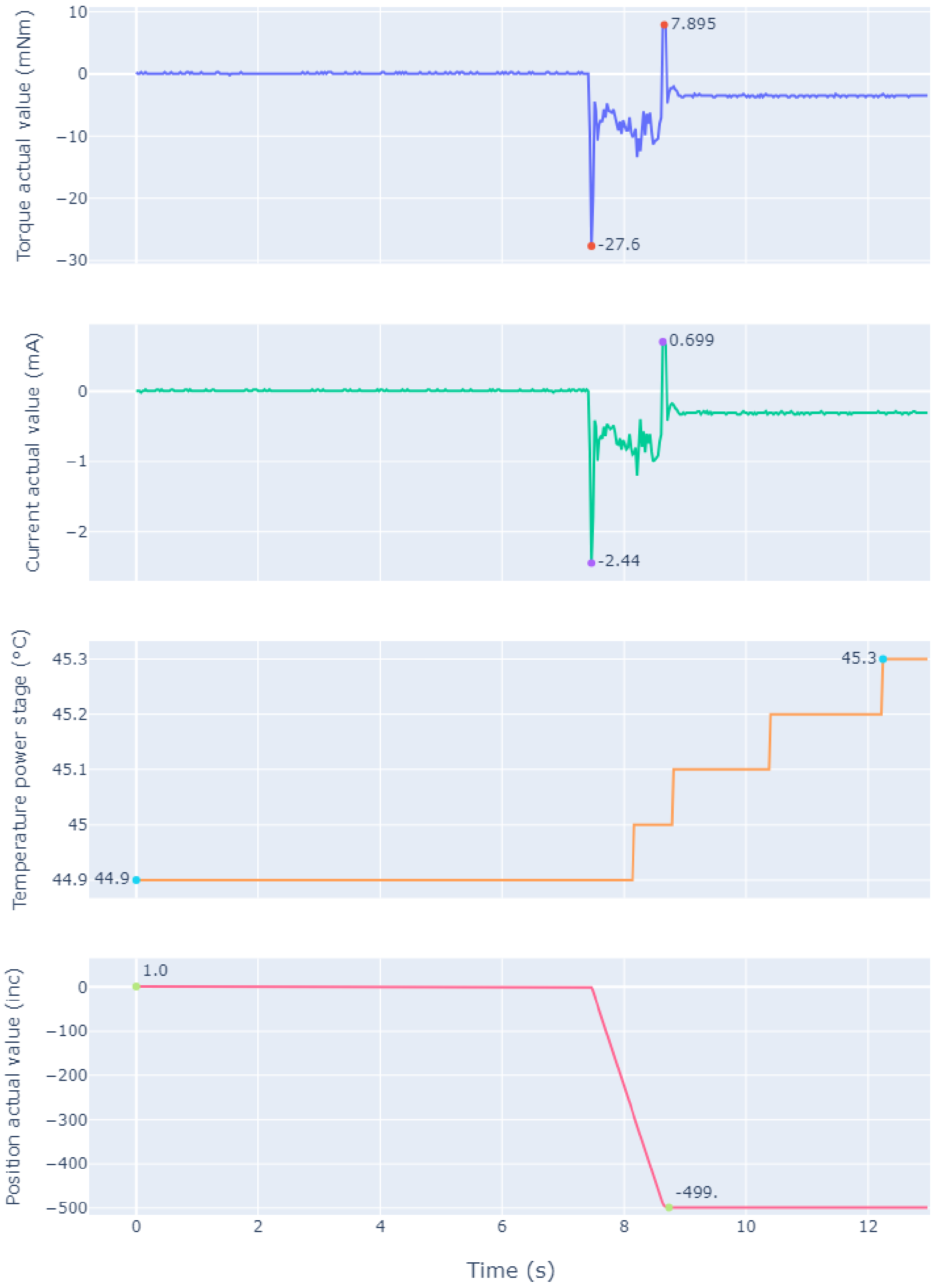
This plot shows the torque, current, velocity, and position for the final version of the EC60 with brakes, going to a specific position with a fast ramp mode under no load in a counter clockwise movement.



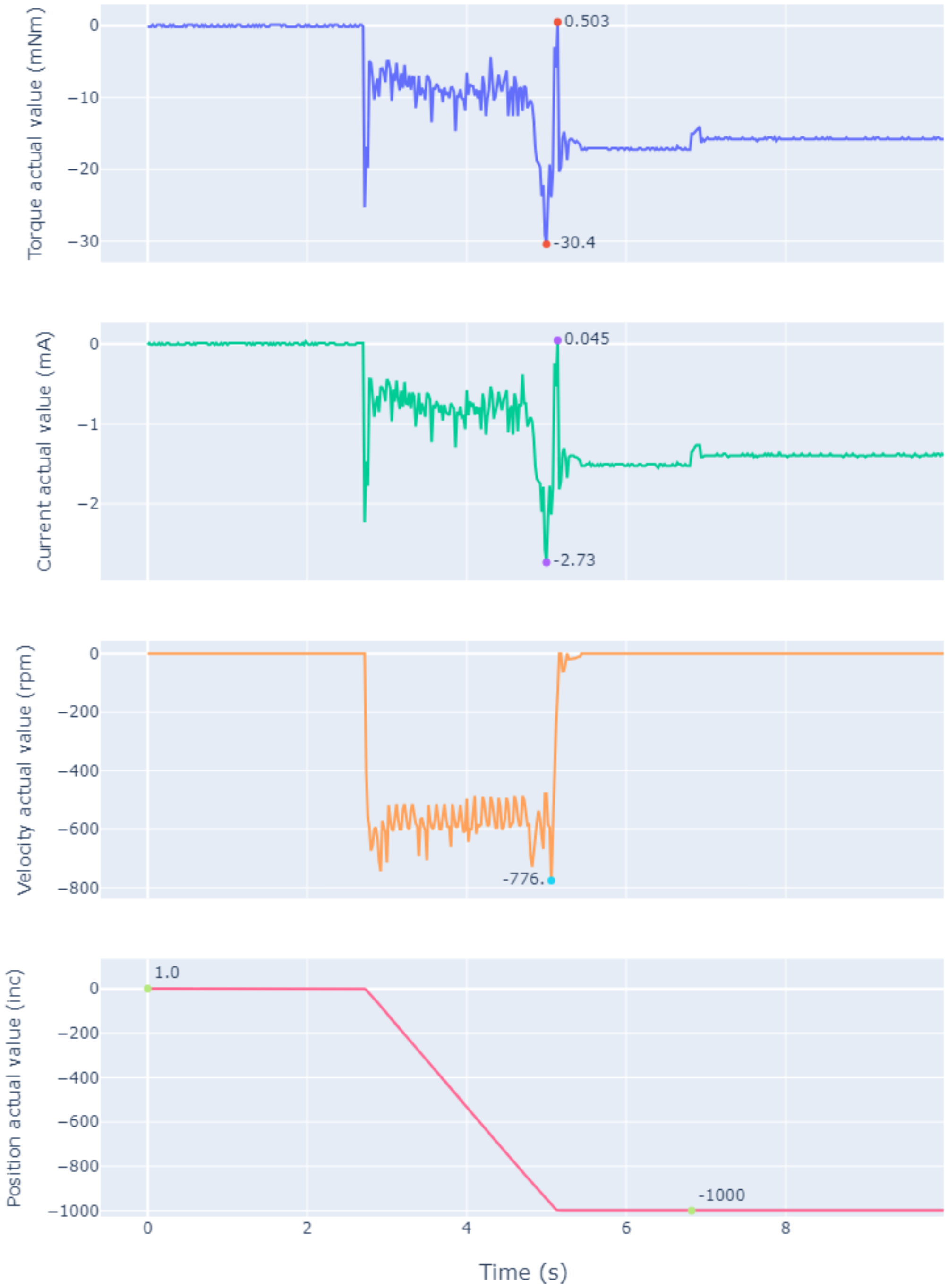
This plot shows the torque, current, temperature, and position for the final version of the EC60 with brakes, going to a specific position with a slow ramp mode under no load in a clockwise movement.



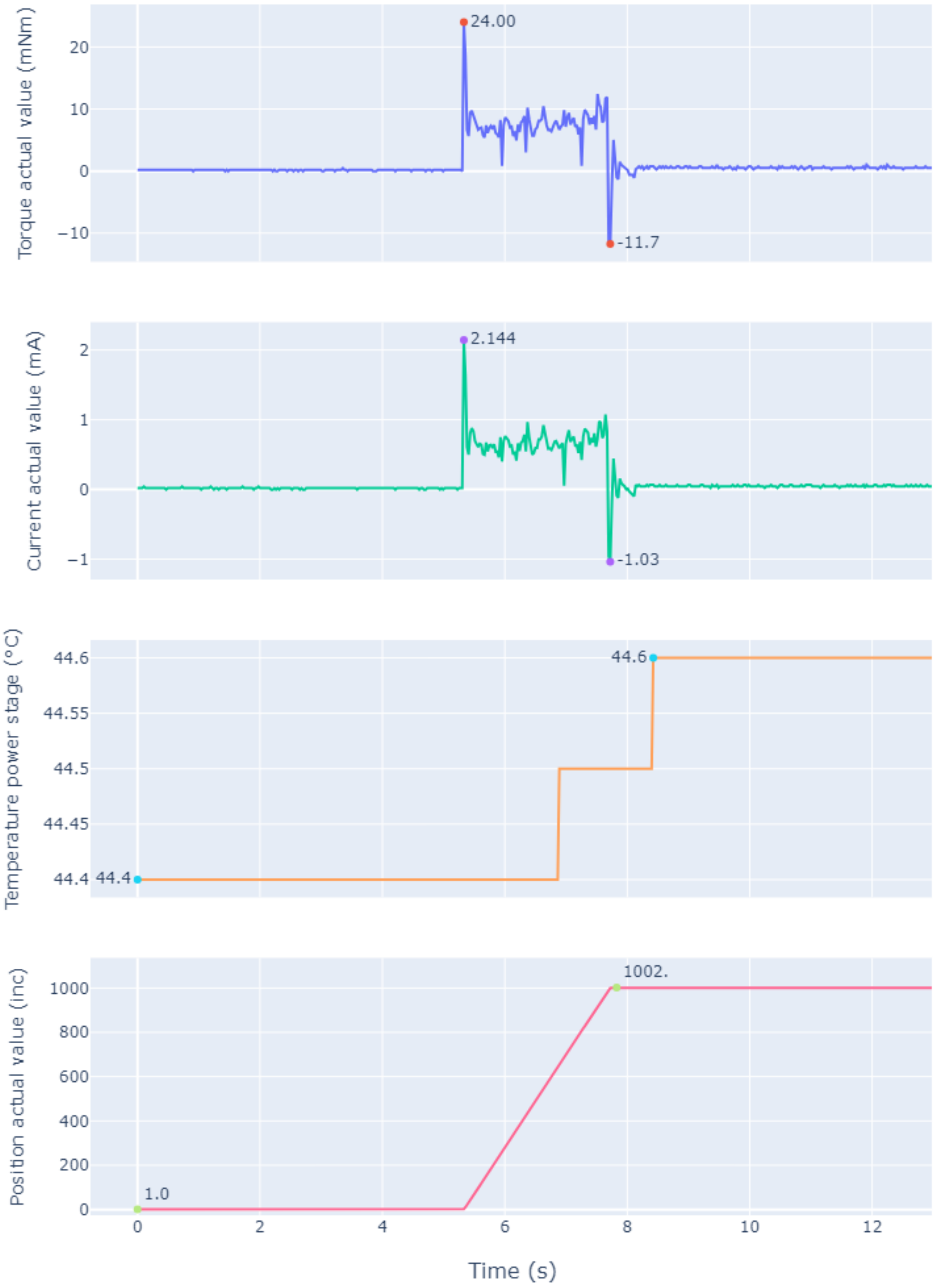
This plot shows the current demand and actual value, velocity, and position for the final version of the EC60 with brakes, going to a specific position with a step mode under no load in a counter clockwise movement.



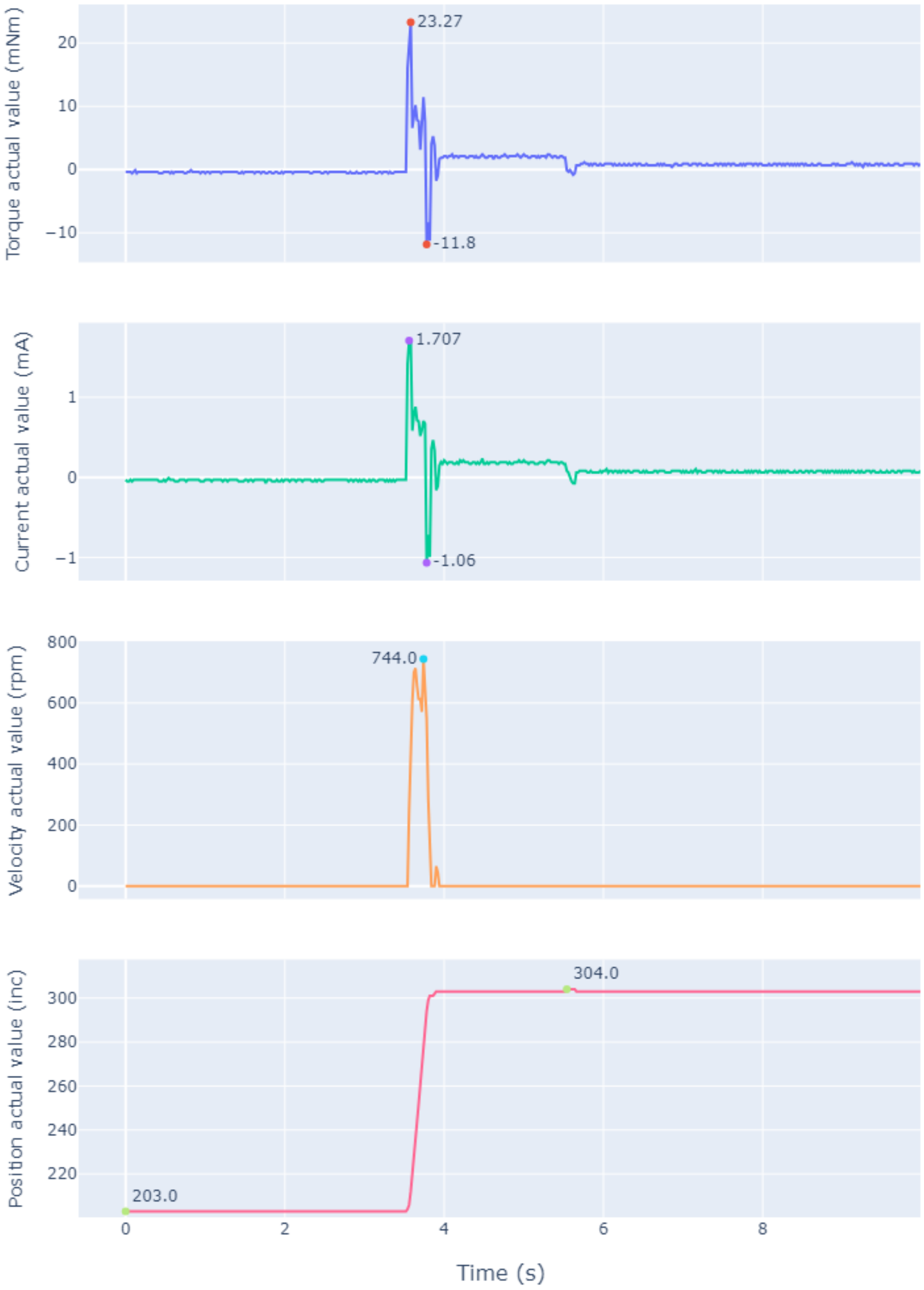
This plot shows the torque, current, temperature, and position for the final version of the EC60 with brakes, going to a specific position with a step mode under no load in a clockwise movement.



This plot shows the torque, current, velocity, and position for the final version of the EC60 with brakes, going to a specific position with a fast ramp mode under no load in a clockwise movement.



This plot shows the torque, current, temperature, and position for the final version of the EC60 with brakes, going to a specific position with a fast ramp mode under no load in a clockwise movement.



This plot shows the torque, current, velocity, and position for the final version of the EC60 with brakes, going to a specific position with a step mode under no load in a clockwise movement.

Appendix L Simulations Figures

Figure 45: Von Mises Stress, Static nodal stress plot, deformation scale 4,187.56.

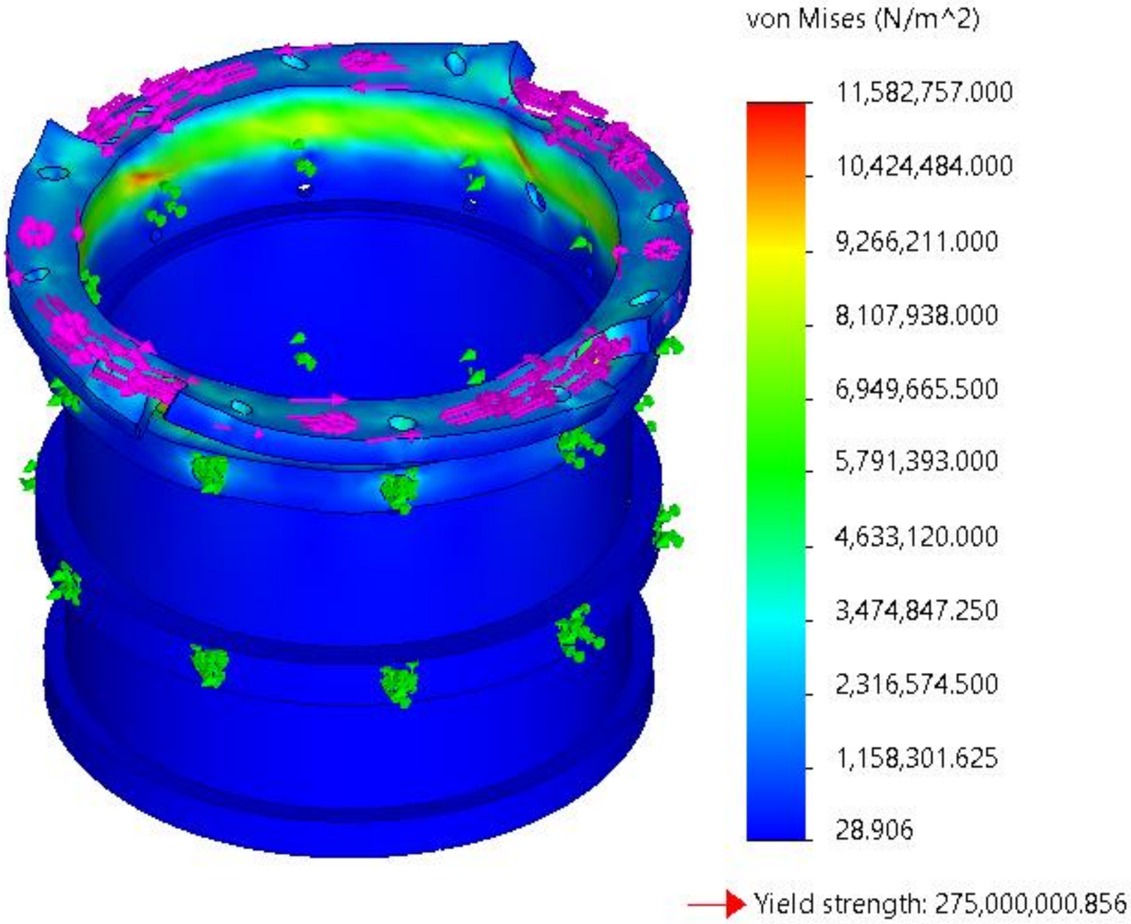


Figure 46: Static displacement, deformation scale 4,187.56.

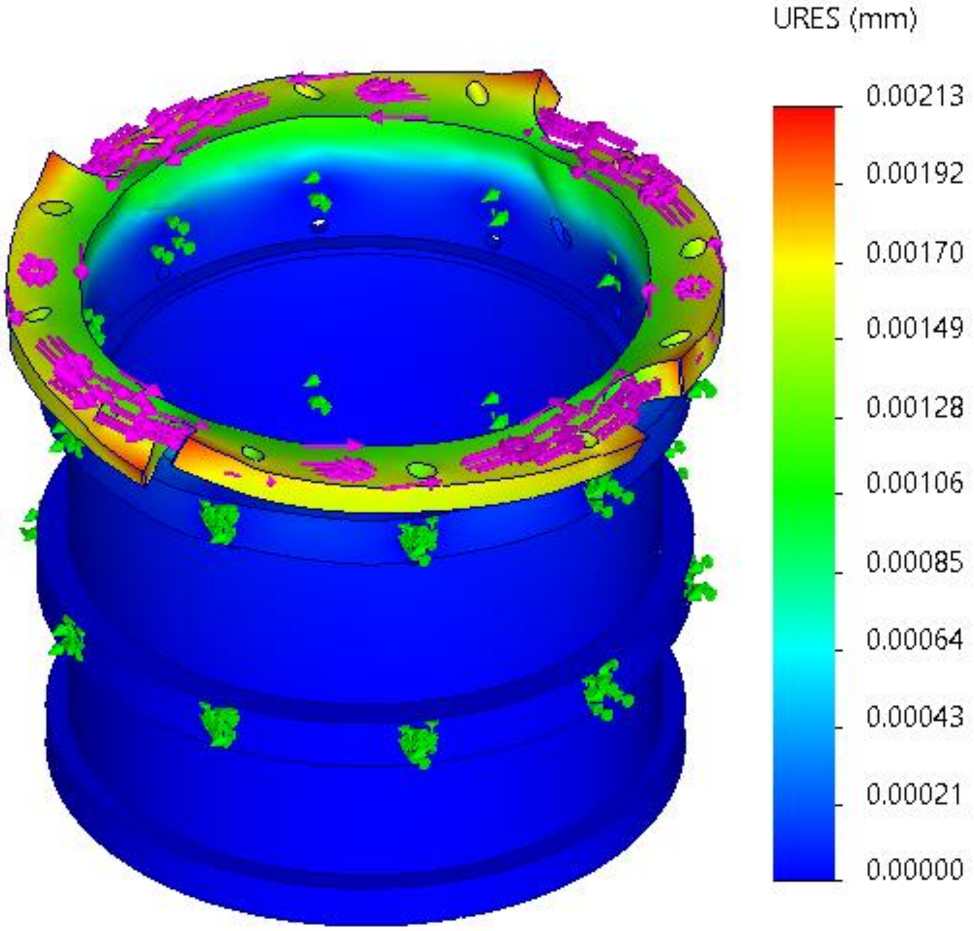


Figure 47: Static Strain Plot, deformation scale 4,187.56.

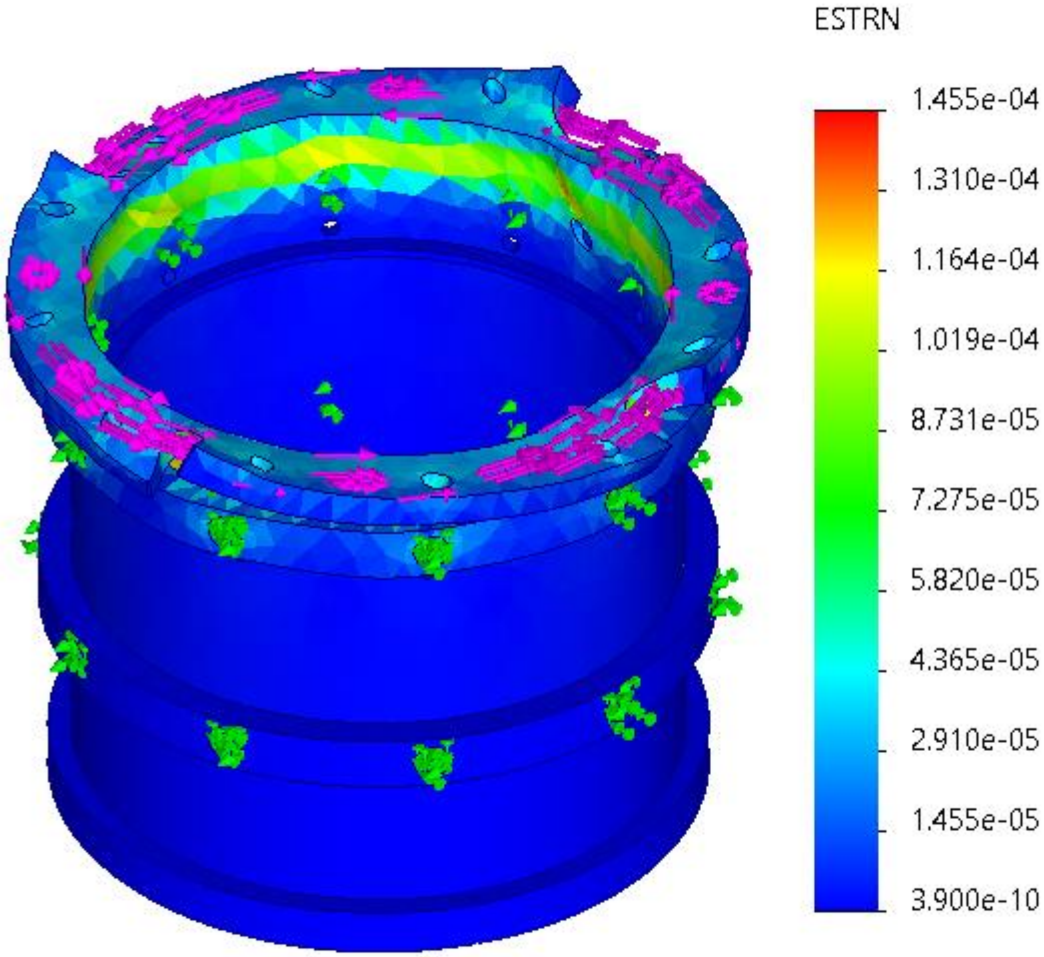
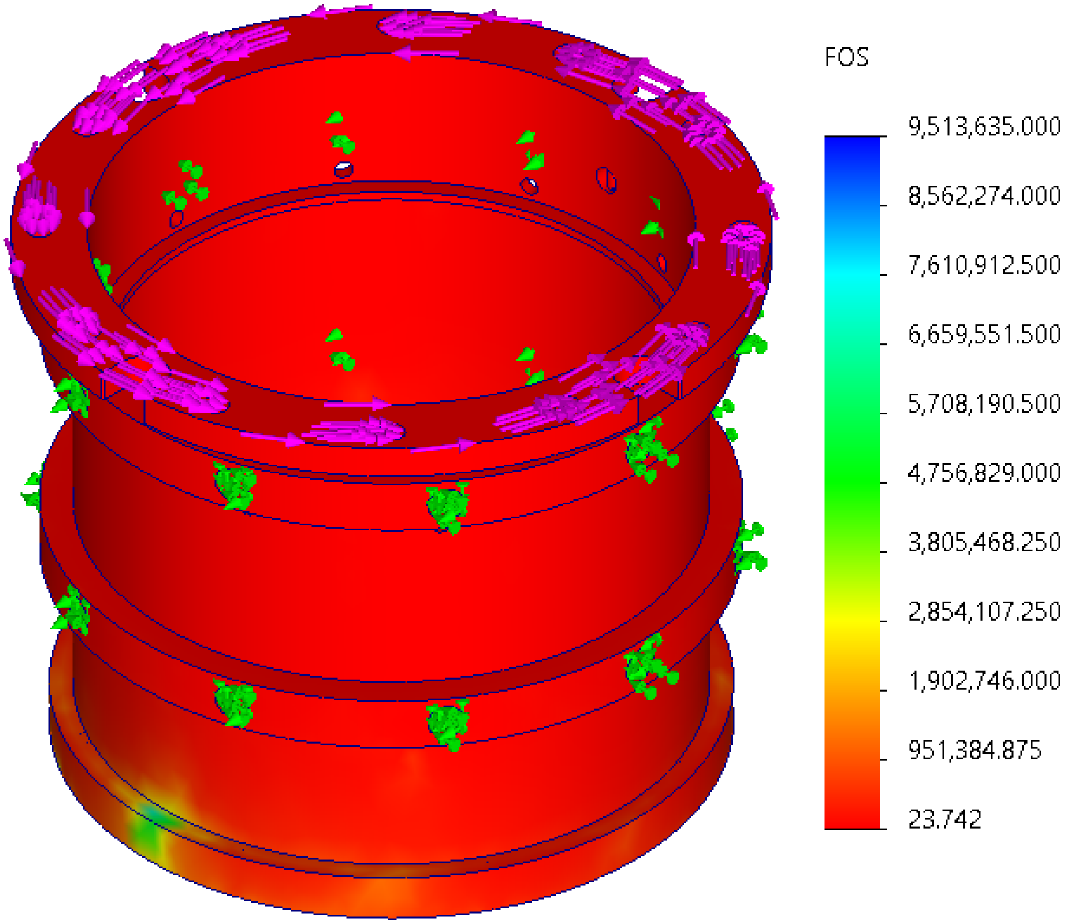
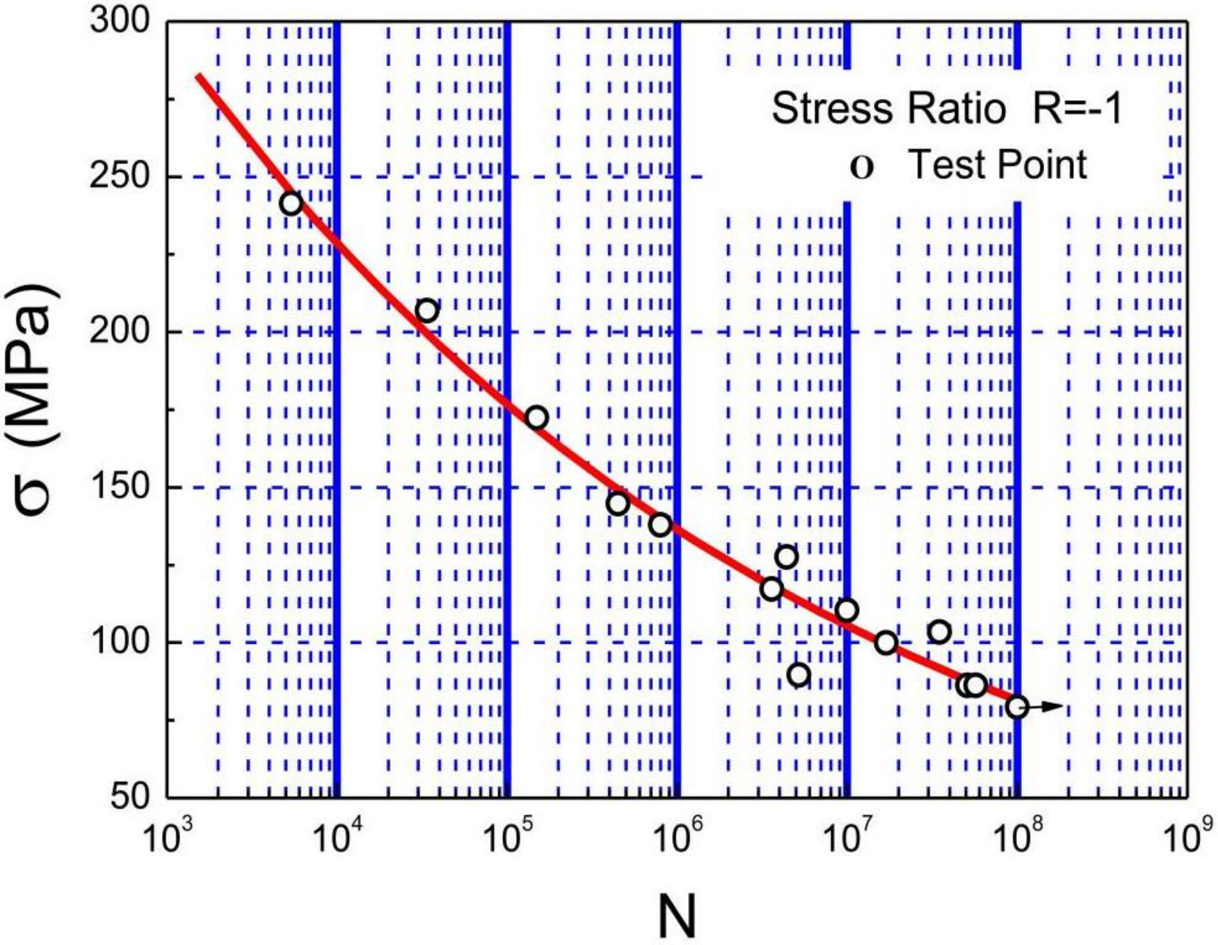


Figure 48: Factor of Safety, criterion: Max von Mises Stress.



Appendix M S-N curve of Aluminum 6061-T6



Reproduced from [91].

Table 28: S-N approximate values for Aluminum 6061-T6.

N (Cycles)	O (MPa)
2000	275
10000	232.5
100000	179.5
1000000	138
10000000	106.5
60000000	87.5
100000000	82