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Design Actuator Control Unit for Aerospace Applications: Automatic Closed-Loop Control for Permanent Magnet Brushless DC Motors

Mohamed Emara, *MIEEE*, James Rennie, Ron Wilkes, Mohamed Darwish, Maysam Abbod, *SMIEEE*

***Abstract*—Actuators are the building block for every automated system. The field of applications is wide open, from home appliances to aerospace. In this joint project between OTM Servo Mechanism and Brunel University London, we design and develop custom-tailored actuators for the aerospace industry. Actuators at aerospace specifications are suitable for many applications, such as aeroplanes and unmanned aerial vehicles (UAV). The design requires significant considerations of the hosting working environment and size and weight constraints. This paper discusses the design, model and simulation of an actuator control unit (ACU) for an electromechanical actuator driven by a 51mm airborne three-phase brushless DC motor. By modelling and simulating the whole system, we can set and tune the control modes of the controller. The ACU comprises the controller and necessary components to complete the automatic control process. We rely on a set of feedback control loops to meet the desired setpoints for the employed actuator despite the applied load and disturbances. Electromechanical actuators are an excellent fit for all-electric systems that require new developments in the field of automatically controlled actuators.**

Index Terms—Electromechanical actuator, Brushless DC Motor, Aerospace, Automatic Control, Actuator Control Unit.

I. INTRODUCTION

THE construction of automated machines has fascinated humankind ever since. The main building block of an automated system is the actuator, which can be defined as a reliable unit responsible for generating a repeatable linear or rotary mechanical movement in accordance with a set of instructions [1]. At the heart of electromechanical actuators lies the electric motor that can be found everywhere, from toys to large machines, with a power that varies from a few watts to a megawatt range [2, 3].

Actuators consist of (i) a controller that commands and (ii) a motor to perform reliable, repeatable, precise actions. The generated mechanical power of the motor's shaft could be adjusted in terms of speed and torque by a gearbox. The controller relies on a group of sensors to guide it through the control process to meet the desired setpoints.

From a driving point of view, actuators are classified into geared and direct drive. In this work, we are more concerned with designing and developing the actuator control unit (ACU) for a bespoke geared electromechanical actuator.

The ACU comprises the controller, driver, powering board, sensors, and interfacing circuitries. The primary mission of the ACU is to maintain the actuator's output shaft speed at the desired setpoint despite the applied load. The ACU is fitted into the compartment of the actuator that offers the controller partial protection from the working environment. From the ACU compartment, the controller communicates with the external world through sensors and interfacing circuits, and in a capacity to command the motor through the driver. The powering board supplies the controller as well as the driver.

Automatic control has played a vital role in developing many sectors, for example, space-vehicle systems, guidance systems, robotics, and industrial production lines. In the controller's design, we follow the principles of automatic control for guiding the whole actuator as a unit in performing its task despite external stimulus and without human interference. The target of the control process is to keep the speed of the actuator's output shaft at the setpoint despite the applied load and other disturbances such as friction and temperature. The speed of the output shaft is regulated by a generated Pulse-width modulation (PWM) signal by the controller.

The motor inside an actuator is the interfacing point between electronics and mechanics, where the conversion from electrical power to mechanical power happens. The electric motor is characterised by the torque constant (Nm/A) value that provides the designer with a good indication of the motor's rated torque and speed. Different types of electric motors can be classified into two main groups according to the driving power source: alternating current (AC) motor and direct current (DC) motor, as shown in Fig. 1. Despite the different types of motors, nearly all motors exploit the generated force from placing a current-carrying conductor into a magnetic field [2],

$$F = B.I.L \qquad (1)$$

Where F is force on a wire of length L, carrying a current I and exposed to a uniform magnetic flux density B. The magnitude of the generated force depends directly on the

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M. Emara is with the Electronics and Electrical Engineering (EEE) Department, Brunel University London, Uxbridge UB8 3PH, London, UK, and also with the Design Department, OTM Servo Mechanism Ltd, Egham TW20 9AL, Surrey, UK (e-mail: mohamed.emara@brunel.ac.uk, mohamedemara@otmservo.com). J. Rennie and R. Wilkes are with the Design Department, OTM Servo Mechanism Ltd, Egham TW20 9AL, Surrey, UK (jamesrennie@otmservo.com). M. Darwish and M. Abbod are with the Electronics and Electrical Engineering (EEE) Department, Brunel University London, Uxbridge UB8 3PH, London, UK (email: maysam.abbo@brunel.ac.uk).

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strength of the magnetic field and the flowing current on the wire. One of the classifications for sorting the motor types is the magnetic field source, which could be a coil carrying current to produce flux in terms of magnetomotive force (m.m.f) or a permanent magnet. The most recently developed, the permanent magnet brushless DC (BLDC), the scope of this work, is hard to be sharply classified. From a configuration and structural perspective; BLDC is a closer fit to permanent magnet synchronous motor (PMSM) category. PMSMs require supply only to the stator. Since the attached magnet to the rotor provides a uniform magnetic field. This opens the discussion to another classification of permanent magnet machines: surface mounted permanent magnet motor (SPM) and interior permanent magnet motor (IPM). Since it is a speed application, in this work, we are relying on IPM motors, in which the permanent magnet is embedded inside the rotor itself.

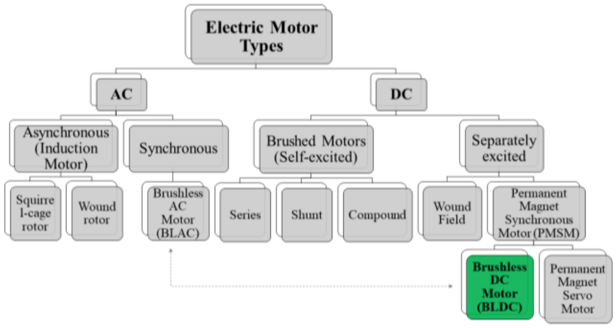

Figure 1. Types of Electric Motors.

II. SYSTEM DESIGN

The design of the ACU is based on developing a closed-loop control system to maintain the relationship between the motor's current position (i.e., output) and the desired position (i.e., input). Despite the applied load, the transfer from the initial point to the desired end is at a constant speed (i.e., setpoint). The controller compares the input and the output to get the difference (i.e., error) and guides the motor through a process to reach the targeted position according to the setpoint. Implementing the proposed system needs working on the following axes: (i) Modelling and simulating the actuator on MATLAB-SIMULINK; (ii) Hardware and firmware development. In this work, the controller relies on two modes to determine the value of the controller output: proportional (P) mode and integral (I) mode. Both modes collectively form a parallel ideal PI controller for calculating the controller's output according to the feedback (see Fig. 2). PI modes work on controlling the error and hit the setpoint smoothly and steadily.

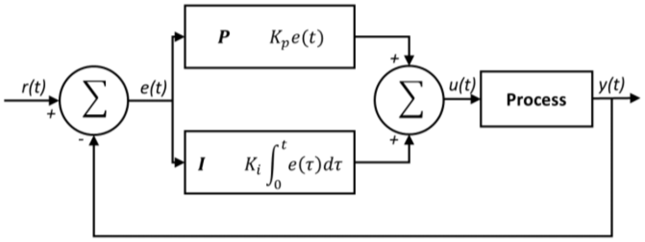

Figure 2. Block diagram of an ideal Proportional-Integral (PI) controller with a feedback loop. y(t) is the process value measured at the output of the process. r(t) is the setpoint and e(t) is the error that needs to be managed. The final output of the controller is a duty cycle that regulates the supplied voltage to the motor phases in accordance with the applied load (i.e., torque) and the desired setpoint.

All action here is performed by Ø51mm in runner interior permanent magnet BLDC motor (see Fig. 3) due to the nature of the application that is primarily a speed control with a varying applied load. BLDCs have high speed-torque characteristics and high-power density. Table I and Table II exhibit the main specifications of the employed-here motor and the actuator as a whole unit, respectively.

The controller takes decision according to the received signals from the feedback loops: speed, current, and position. Fig. 4 exhibits the block diagram of the ACU. The motor receives commands from the controller through the driver. The powering board supplies the driver and all the rest of electrical components.

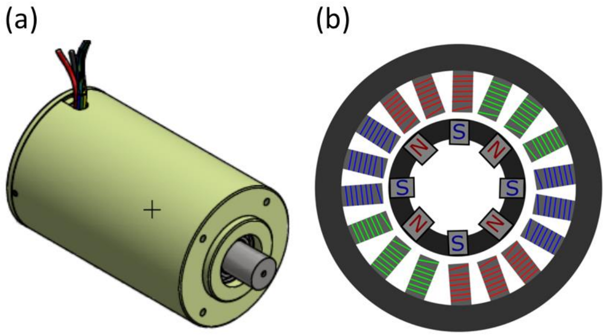

Figure 3. OTM Ø51mm airborne brushless DC motor. **(a)** 3D model of the OTM motor. Colour-coded leads represents motor's three phases and hall sensor leads. **(b)** BLDC motor is consisting of 8 poles and 18 sectors and can generate rated torque up to 0.35 Nm, at rated speed, 3500 RPM. The three phases of the motor are connected to a star point.

TABLE I AIRBORNE OTM BLDC MOTOR SPECIFICATIONS.

No of Poles	8
No of Phases	3
Rated Speed	3500 RPM
Rated Torque	0.35 Nm
Terminal Resistance	0.082 Ω
Line to Line Inductance	0.038 mH
Max Peak Current	15 A
Commutation	Hall Sensors
Motor Control Topology	Trapezoidal
Operating Temperature	-45/+85 ℃

TABLE II ACTUATOR SPECIFICATIONS.

Load Range	5-21 Nm
Nominal operating torque	18 Nm
Desired speed of operation (setpoint)	20 RPM
Maximum Current Consumption	4.5 A
Operating Voltage	24 VDC
Number of rotations for full travel	~6

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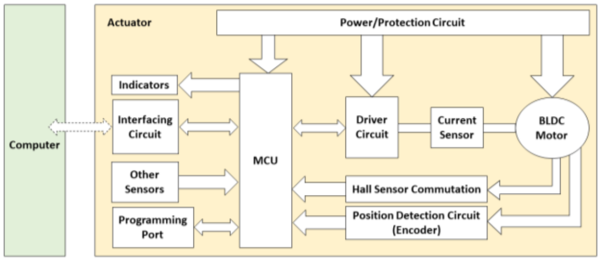

Figure 4. Block diagram of the actuator control unit (ACU). Powering board at the top is responsible for feeding the different components of ACU and offering protecting against the working environment from an electrical point of view. The ACU is tunned and programmed by a computer through the interfacing circuit.

A. *Modelling and Simulation*

The theme of the control process in this project is the speed control of the actuator's output shaft by employing a PI controller (see Fig. 5). The applied load (i.e., Torque) to the output shaft is the process variable; the controller's function is to keep the speed of the output shaft at the setpoint. The whole system, comprising electrical and mechanical items, has been modelled on MATLAB & SIMULINK to tune the control parameters and set the proper control modes (see Fig. 6). A torque source was used to apply different loads against the actuator's output shaft during the process. The final tunned parameters of the control modes are embedded into the firmware. Fig. 7 exhibits the speed of the actuator's output shaft at different applied loads to the system. The generated duty cycle (i.e., PWM) by the controller is responsible for regulating the supplied voltage to the motor's phases in response to the applied load (see Fig. 8). The effective current level of the motor phases changes as well in a direct proportion with the applied load (see Fig. 9).

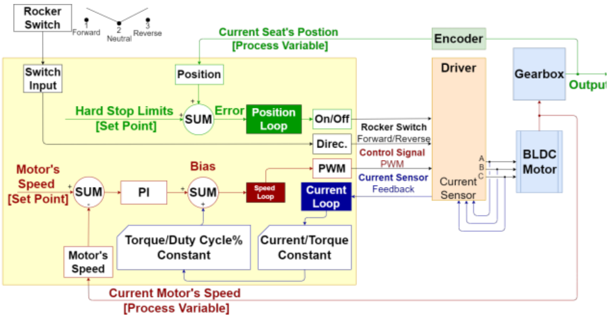

Figure 5. Implementation of PI controller for an aerospace actuator. Feedback loops work together to provide the controller with the right information to maintain the speed of the actuator's output shaft despite of applied load and disturbances.

B. *Hardware Development*

There are many options for implementing the control theory and developing the controller, such as application-specific integrated circuits (ASIC), field-programmable gate array (FBGA), a microcontroller unit (MCU), and digital signal processor (DSP). MCU was selected, programmed according to the control process, and hosted by a printed circuit board (PCB). The output of the MCU controls the motor's behaviour. The firmware code was written in the C language; a compiler transfers the code instructions into the machine language to be loaded to the microcontroller. The controller's parameters for the closed-loop control are retrieved from the system's model on MATLAB & SIMULINK. Fig. 10 depicts a 3D model of the designed actuator.

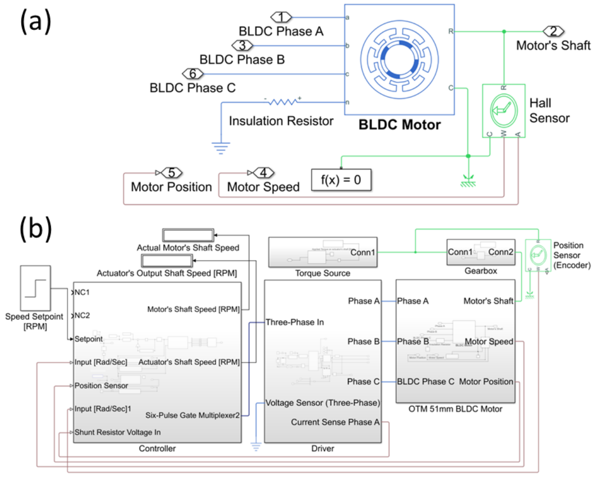

Figure 6. MATLAB & SIMULINK model of the actuator. (a) Model of OTM brushless DC motor. (b) Whole system for simulating the performance of the actuator with a gearbox and torque source to apply loads with different levels to the actuator's output shaft.

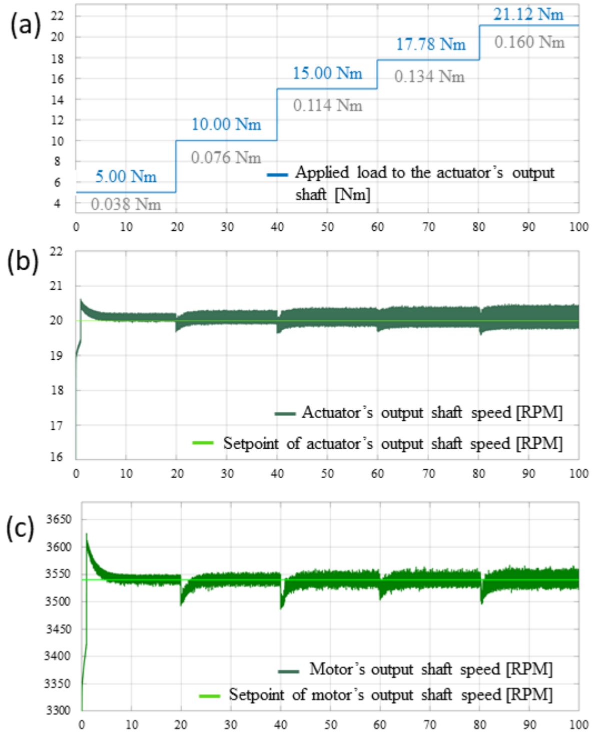

Figure 7. Results from the modelled system on MATLAB & SIMULINK: output speed at different applied loads to the actuators' output shaft. (a) Applying different load levels—values in grey are the corresponding applied torque to the motor's shaft through the gearbox. (b-c) Speed graph for both the actuator and embedded motor. The slope that begins at 0 and lasts for almost one second is due to the installed pre-charge circuit for a smooth current transition.

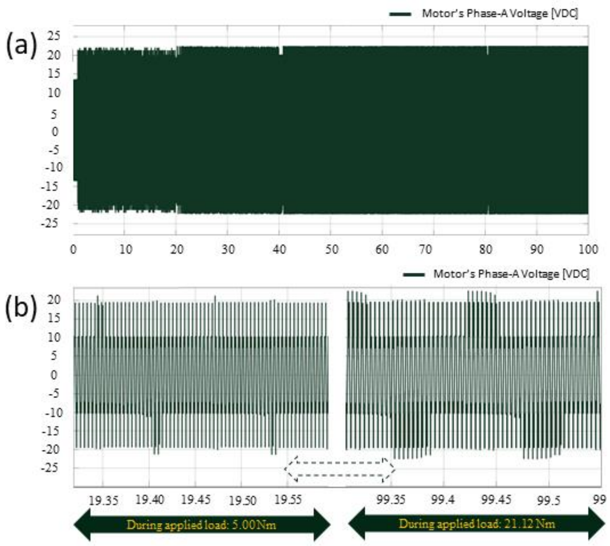

Figure 8. Motor's Phase-A voltage during the same control scenario of Fig. 7. (a) During the simulation, motor's phases were supplied by the rated 22-VDC. (b) Generated duty cycle by the controller is regulated in response to the applied load to maintain the speed of the actuator's output shaft at the desired setpoint. Generated duty cycle is directly proportional with the applied load.

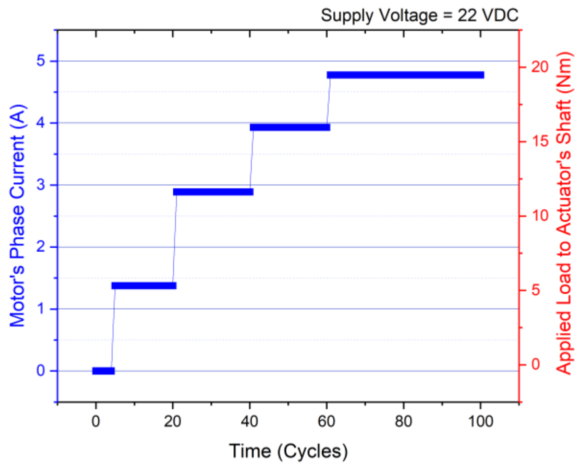

Figure 9. Effective current (A) of a motor phase at different applied loads.

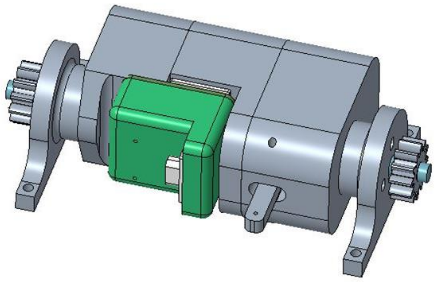

Figure 10. 3D model of the OTM dual shaft electromechanical actuator. The ACU's compartment is highlighted in green, which is detachable from the actuator's body. The actuator gets power through the mounted connector on the ACU compartment. The actuator operates as a compact unit that contains all needed sensors to complete the feedback loops for a fully automated control process.

III. DISCUSSION

This work presents the design, model, and simulation results of the ACU of a bespoke actuator for an aerospace application. Fig. 11 summarises the characteristics of both the actuator and the employed brushless DC motor. The performance of the automatic control process can be assessed by reviewing Fig. 12. The automatic system takes around 3.5 seconds to settle at the desired setpoint. The maximum recorded steady-state error is ±0.3. The initial overshoot percentage is 3% higher than the setpoint of the actuator's output shaft speed.

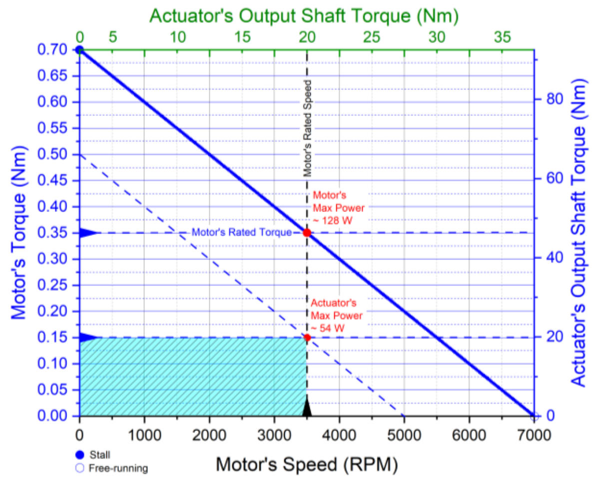

Figure 11. Characterisation graph of both the OTM Ø51mm airborne brushless DC motor and the developed actuator. Cyan coloured box highlights the actuator's active region. The motor shaft is plugged to a gearbox with the following ratio: 176.2:1. Speed setpoint at the actuators output shaft is 20 RPM. The controller by regulating the supplied duty cycle to the motor, can maintain the desired speed despite the applied loads, within the capabilities of the employed motor.

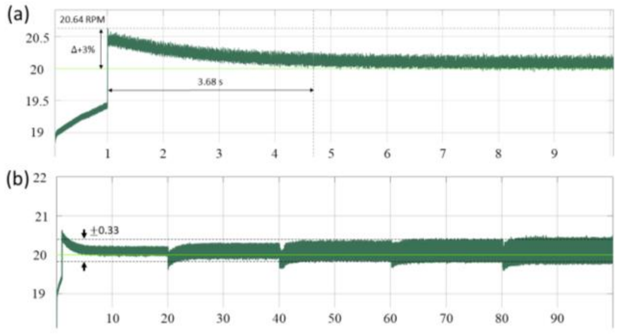

Figure 12. Characterisation of actuator's output shaft speed at varying applied load levels (5 up to 21.12 Nm). (a) Overshoot value is 3% higher than the steady-state value (20 RPM). (b) The maximum recorded steady-state error is around ±0.3.

When commercial solutions cannot fulfil the desired objectives, it is time to develop a custom-tailored actuator. Off-the-shelf solutions may look convenient from a budget and lead time point of view. However, they cost more in the long run, with a higher probability of clashing with legislation and IP rights.

The ACU is the highest authority unit within the actuator itself; however, it could be a slave among other slaves in an extended automated system such as a quadruped robot [4, 5] or an assembly robotic arm [6]. In robotics, for instance, each joint gives an extra degree of freedom (DoF) to the robot's mobility. Each joint is represented by an actuator; its ACU receives commands from a master computer through serial communication protocols. The master computer in this scenario is responsible for orchestrating all the actuators (i.e., slaves) to produce meaningful actions. An actuator for a robot is similar to a muscle for a human that receives commands from the brain over a complex network of nerves [7]. The same applies in aerospace applications; however, with a computer flight controller instead of the master computer.

A. Types of Actuators

Actuators come in different sizes and specifications to serve various fields such as medical [8, 9], aerospace [10-12], and robotics [13, 14]. According to the application area, developed actuators should meet design considerations and overcome technical challenges in terms of size, weight, power and working environment constraints. For instance, size and weight in aerospace applications and field robots are vital. Since reducing the total weight of the hardware means increasing the payload, which in terms of finance and operating cost can be translated into less fuel consumption—or longer battery life, or additional cargo. The industrial market is full of types of actuators [15, 16] that can be classified into one of the following groups: pneumatic [17], hydraulic[18, 19], and electric[20]. The classification factor between the three different groups is the used driving force that generates the needed mechanical power to act over the actuators' output shaft (see Table III).

A. Electromechanical Actuators

Electronics do not significantly influence the weight of the actuator; however, they may affect the total size of the actuator and the allocated space. In electromechanical actuators, electronics and electrical circuits are directly responsible for the actuator's performance, whether it is an athletic performance or a high endurance one.

Aerospace actuators are exposed to a wide range of temperatures and environmental conditions and must be able to maintain the same performance. Fig. 10 shows that the electronics are protected inside a metal compartment; however, the temperature occasionally may go beyond the threshold. All of that must be considered in addition to the expected shelf-life of the actuator.

Developing electromechanical actuators aligns with the international efforts to limit or eliminate fossil fuel dependence index to reduce carbon emissions. Electromechanical actuators reduce the direct use of oil in comparison to hydraulic systems. Oil, the force-fluid in a hydraulic actuator, requires periodic refills and replacements, which needs dismounting of the whole system and complete attention to air intrusion inside the pipes of the hydraulic circuits. Running air bubbles inside the hydraulic circuit is dangerous for the actuator (e.g., valves) as a unit and the hydraulic power unit (HPU). A routine check of seals and filters is a must to avoid frequent oil leaks in most cases. Moreover, electromechanical actuators are more efficient in electrical-to-mechanical power conversion [16, 21].

Electric motors produce small torque to their size and weight. On the contrary, hydraulic actuators have an excellent force-to-weight ratio. Thus, hydraulic actuators are usually nominated to take more athletic roles, such as the employment in hydraulic humanoid robots [22, 23]. The rated torque of the employed-here motor is around 0.35 Nm, while the required nominal operating torque at the output shaft is 18 Nm. Therefore, a reduction gear is necessary to fill the gap between the two torque values. However, gears reduce the power transmission efficiency and introduce friction and backlash. Gears are increasingly considered the weakest point in an electrical system [24].

IV. CONCLUSION

We demonstrate the design of the ACU for a bespoke electromechanical actuator. The design is a push forward to all-electric systems that require new developments in the field of automatically controlled actuators. Actuators that meet the specification of aerospace applications are suitable for both aircraft and unmanned aerial vehicles (UAV). The controller of the presented system here applies the PI modes to maintain the speed of the actuator's output shaft despite the applied loads. The actuator is driven by a brushless DC motor. The controller is fed by three feedback loops: speed, position, and current consumption. The controller is tuneable and programable by a computer through an interfacing circuit inside the ACU. We have gathered preliminary results by applying the same control scenario to a Model Predictive Control (MPC) in a future work. Hence, a careful design of the gearbox is needed, in addition to a full understanding of the nature of the application and the working environment.

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TABLE III COMPARISON BETWEEN DIFFERENT TYPES OF ACTUATORS. (COLLECTED DATA FROM [16, 21, 25, 26])

Property	**Electric**	**Hydraulic**	**Pneumatic**
System Design	Controller, driver, solid stat logic, power MOSFETs.	Pump, pressure regulators, accumulators, valves, filters, coolers	Compressors, pressure controllers, filters, mufflers, valves
Power Supply	Electric power sources and batteries. The voltage range depends on the field of application; it may vary from a few volts to 460 VDC.	Hydraulic power units are based on the used solution, either oil, water, or synthetic liquids. The pressure value, roughly varies from 0.4 to 70 MPa.	Compressors based on the used gas either, air nitrogen. The pressure value roughly varies from 0.04 to 0.9 MPa.
Features	**High efficiency~90%** of the electrical power is converted to mechanical power. Low sensitivity to the ambient temperature; considering the operating temperature of each component and the need for adding extra active or passive (e.g., heat dissipators) colling items (e.g., fans). Low force-to-weight ratio. The motor's shaft and gearbox combination may enhance the situation.	The average efficiency of around 60% of the generated power is transferred to the output mechanical shaft. Low sensitivity to the ambient temperature, considering the viscosity of the pressurised solution is inversely proportional with the temperature. Coolers and radiators may be required for long durations of operation. Excellent force-to-weight ratio due to the capability of the system to generate very high pressure.	The least efficiency among the three categories, around 30%. Very sensitive to the ambient temperature. Has a fair force-to-weight ratio. The system in total has a lightweight.
Sensors to feed the feedback loops	1. Encoder (i.e., Position sensors) 2. Current sensors 3. Hall sensors. 4. Temperature sensors	1. Encoder (i.e., position sensors) 2. Current sensors 3. Hall sensors. 4. Temperature sensors 5. Pressure sensors	1. Encoder (i.e., position sensors) 2. Temperature sensors 3. Pressure sensors
Cost	The total cost of an electric system is relatively lower than a hydraulic one.	The most expensive solution among the three categories.	Low cost.
Field of applications	The field of applications is wide from home appliances to aerospace applications. Supported by different motors that suits various applications: speed, precisions and low consumption demands. Also, electric actuators are supported by the current advances in battery development technologies, which improve the generated output power (Watt) and the capacity (Ampere-Hour).	It is quite noisy. More suitable for applications that require an athletic performance (i.e., excellent force to weight ratio), and noise may not be an issue for automotive applications, robotics, and production lines.	More suitable than the two other categories for hazardous areas that host sources of release of flammable gases and vapours such as aircraft hangers and Oil & Gas sites. In these sites ignition sources such as mechanical machinery or electrical equipment must be kept distant according to the zone code. For such applications, the pneumatic system may outshine the two other types.