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VARIOUS OPERATION MODE OF CONSTRUCTION MACHINERY USING ENERGY OBTAINED FROM RENEWABLE SOURCES

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Abstract: *The aim of the paper is to outline the potential solutions for operation of construction machinery using energy obtained from renewable sources. "Green" machines for construction have zero-emissions and are silent, therefore they are recommended to be used in the urban environment. This paper presents the proposed platform for the experimental study carried out in order to use solar energy as an energy source, which is stored in batteries with various capacities and its direct use in processes with energy consumption fluctuations, such as soil digging process.*

Keywords: *Renewable sources, construction machineries, energy efficiency, environment*

1. Introduction

Importance of the subject from a scientific, technologic, socio-economic or cultural point of view. Within the context of global warming, the energy crisis and the ever-increasing price of petroleum, there is a need to reduce the energy consumption and pollution of construction machinery. The current geopolitical context imposes the reduction of our dependency on fossil fuels and the identification of alternative solutions for the actuation of construction machinery. In order to fulfill these requirements, we can look towards the field of automobile development, where a variety of actuation solutions are currently being studied, some purely electrical and some hybrid. Some of these solutions can also be applied to construction equipment – one prime example being the hybrid excavator. Electric actuation technologies have become increasingly popular in the field of construction equipment over the past few years, with them being increasingly able of providing the necessary power, functional safety and reliability for such applications, while also offering reduced fossil fuel consumption and lowered pollution. Studies have been conducted on purely electrically actuated construction machinery systems, which are based on energy storage units (ESUs) and electromotors (EMs). In order to ensure a high enough autonomy of the equipment and proper dynamic performance under shocks, both the ESU and the EM need to have high energy capacity and power. Table 1 lists the characteristics of the most usual ESUs [1].

Table 1: Energy storage units (ESU)

ESU Type	Pb Battery	Flywheel	Supercondensator	Hydraulic Accumulator (HA)	NI-MH Battery	Li Battery
Specific power (W/kg)	75-300	400-1500	500-5000	2000-19.000	150-200	250-340
Specific energy (Wh/kg)	30-50	10-30	2.5-5.5	2	100-120	75-200
Energy capacity (Wh/L)	50-80	20-80	35	5	150-180	200-500
Nr.of cycles	500-1500	200.000	100.000	100.000	2500	2000-10.000
Efficiency	<80%	≤96%	≤95%	90%	90%	≤95%

2. Analysis of current state-of-the-art within the conetxt of the project's scope

The field of aviation is also strongly oriented towards electrical actuation solutions (usually called PBW – „Power-By-Wire" technologies). These PBW solutions are used to extend the applicability of electrical acuation systems towards aeronautic control systems. A PBW actuation system (fig.1) transports electrical energy between various systems using wires and cables, instead of hydraulic pipes, which increases aircraft performance.

The advantages offered by PBW actuation systems are increased reliability, due to the absence of hydraulic fluids which are flammable, reduced weight, volume and complexity of the energy transfer systems, reduced costs and complexity of maintenance, higher energetic efficiency and improved dynamic characteristics [2].

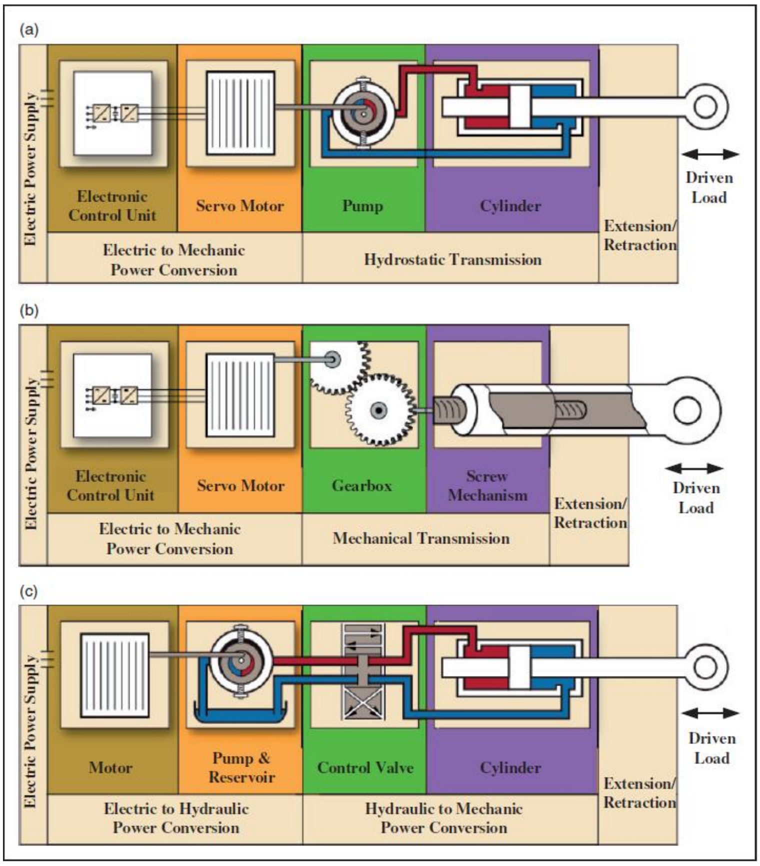

Fig. 1. Actuators using PBW technology: a) EHA, b) EMA, c) HSA

The innovative solution proposed by this project is the use of solar panels as main energy source, storing the energy in accumulators of various capacities (depending on desired autonomy) and using said energy directly for processes with large fluctuations of energy consumption (like digging operations), all without requiring intermediary power sources.

Green construction equipment (which are electrically powered and actuated) have zero polluting emissions [3][4] are far more silent, which would allow them to function continually in densely populated areas, even during night hours, without disturbing the local population [5]. All these characteristics translate to a positive impact to society through increased work efficiency, productivity, functional safety and reduced influence on the environment [6]. A variety of electrically powered and actuated construction equipment is presented in fig. 2-7.

Fig. 2. E10e Mini Excavator

The Bobcat E10e [7] has a state-of-the-art Lithium-Ion, maintenance-free battery pack with an advanced management system, designed to fit within the standard machine envelope to maintain the machine's ZTS profile. Following the daily working routine, the E10e can operate throughout a full 8-hour day, using operator breaks to recharge the batteries. Using an external super-charger functionality, the batteries can be recharged to 80% of battery capacity in around 1 hour. The battery can also be recharged overnight by using the on-board charger from a standard 230V grid. In addition, the new machine is easy to maintain and safe to operate – thanks to the exclusive use of low voltages, there is no need for operators to have special authorization to work with the E10e.

Fig. 3. The 19C-IE electric compact excavator

The new JCB 19C-IE [8] has maintenance free batteries, needs minimal daily checks and requires less servicing, saving rental companies, hirers and owner operators time and money. No engine and associated items significantly reduce servicing time and equipment. No need for emissions extraction saves on wages and equipment. No engine liquids to check saves you time and money. Electricity is a lot cheaper than fossil fuel. The new 19c-1e gives you the freedom to work anywhere, anytime with quick charging and long battery life. The machine's 4 battery pack lets you work for 5 hours on a standard application (equivalent to a full day). 3 charging options: 110V, 230V and 415V let you get to work when and where it suits.
The JCB 19c-1e electric mini excavator generates less noise than many household appliances, making it ideal for urban areas and indoor applications and allowing better communication with co-workers. Noise at the operator station is a huge 10 dB less than the diesel version. It allows for 'out-

of-hours' working, to maximise time on site and speed up the job. The 19C-1E is fitted with a blue light indicator to show the machine is running. Three single flanged bottom rollers allied with short pitch tracks ensure a quiet, smooth ride.
The JCB 19c-1e electric mini excavator is safer for the environment, operators and bystanders, and is ideal for working indoors and in urban areas. Zero emissions and low noise levels make for safer working conditions. The 19C-1E operates completely free of any trailing tethers. JCB's unique 2GO system safely isolates all the controls.

Fig. 4. XCMG Electric Excavator

Cummins collaborated with XCMG [9], the 4th largest construction machinery company in the world, to design and build the 3.5-ton electric excavator, which will serve as a technology demonstrator. Often operating on work sites in densely populated towns and cities around the globe, construction equipment must meet stringent emissions requirements and keep noise and disruption to a minimum while getting the job done. The new electric excavator is suitable for working conditions that require more stringent environmental standards and noise reductions.

Fig. 5. PC30E-5 Mini Electric Excavator

The Komatsu-original electric PC30E-5 [10] achieves a clean work environment. It can be deployed to a diverse range of workplaces, such as indoors, piping work, urban construction, and landscaping. As its power source is an electric motor, this model does not generate loud noise like internal combustion models. Even while the machine is in use, it is easy for the operator to communicate with workers near the machine, which improves workplace safety. This machine can also be deployed at workplaces where you need to consider construction noise, such as residential areas, near the hospitals and at night. Reducing the operator's fatigue, thanks to no engine vibrations. As no internal combustion engine is mounted on this machine, the vibrations which are transmitted to the operator are outstandingly improved. With low levels of stress or fatigue, the operator can perform work comfortably. Making the work environment comfortable by reducing the amount of heat generated Heat generated by the machine is very small, as it has no engines. As it also gives almost no heat around the machine, the machine also helps improve the work environment.

Fig. 6. Volvo ECR25 Electric Excavator

The lower noise levels that the ECR25 Electric offers enable you to work anytime, anywhere – even at night in populated areas [11]. This can lessen the disturbance inner city work can cause and reduce congestion at peak times, all the while increasing your efficiency. It also creates a more pleasant working environment for you and your colleagues with whom you can clearly communicate whilst operating. The ECR25 Electric features a zero-tail swing radius design making it perfect to confidently work in confined spaces. Moreover, thanks to zero emissions, the need for costly fumes extraction systems is eliminated in indoor jobs, such as basement groundworks and building demolition.

Fig. 7. EX02 electric excavator prototype

This opens up new business opportunities which in turn helps optimize utilization • No emission locally • Sound level down tremendously • Maintenance free battery • Low electricity cost • No power consumption when machine not working • Low vibration • Color display with jog wheel navigation • Intuitive and easier to operate • Full LED lighting • Blows less dust • Same performance as its diesel equivalent • Ultimate lifting capacity • Zero-tail swing radius • Front corner stays within tracks width • Wide range of Volvo attachments.
Volvo Construction Equipment (Volvo CE) [3] unveiled its latest concept machine – known as the EX02 – to industry specialists, policymakers, the media and academics at the Volvo Group Innovation Summit on May 2017. The 100% electric compact excavator prototype delivers zero emissions, 10 times higher efficiency, 10 times lower noise levels and reduced total cost of ownership compared to its conventional counterparts. It is believed to be the world's first fully electric compact excavator prototype.
The Volvo Group defines electromobility as 'commercial vehicles and machines that can utilize an electrical motor to propel or to perform the main purpose of the machine'. To make the EX2 prototype fully electric, the combustion engine has been replaced with two lithium-ion batteries, totaling 38KWh, which store enough electric energy to operate the machine for eight hours in an intense application, such as digging compact ground. The hydraulic architecture has also been replaced with electric architecture, which incorporates electromechanical linear actuators that help to optimize the transmission chain. Removing the hydraulic system and the combustion engine, as well as reducing the cooling needs, has led to significantly lower noise levels
The field of electrically actuated construction machinery is new and in continous development. Like in every new domain, there are emergent issues with the large scale implementations of such solutions, due to lack of experience and knowledge related to actuation solutions, energy storage systems, system reliability and lackluster training of maintenance personnel.
For the validation of an electrical actuation system, using solar panels and energy storage units, an experimental stand will be used in order to simulate the actuation of an excavator's arm during digging operations. The characteristics of the experimental stand are presented in fig. 8.

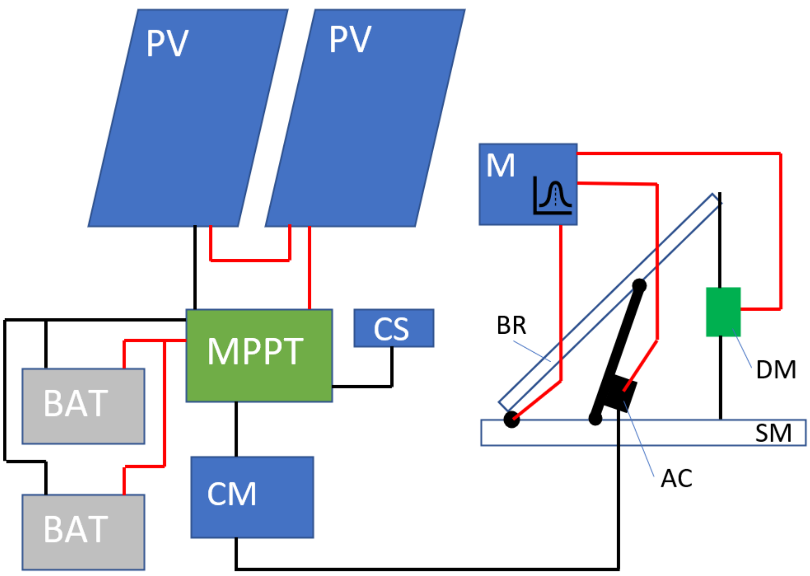

Fig. 8. Experimental Stand

The experimental stand is composed of the following elements (fig. 9-15):

1. PV – photovoltaic monocrystalline solar panels, with a maximum power of 375 W (fig. 9);

Fig. 9. Solar panels

2. BAT –Deep Cycle Gel type electric accumulators, with a 12 V voltage and an energy capacity of 150 Ah (fig. 10);

Fig. 10. Electric accumulator

3. MPPT –SmartSolar type solar charge controller with a maximum voltage of 100V and 50 A current , with Bluetooth connectivity (fig. 11);

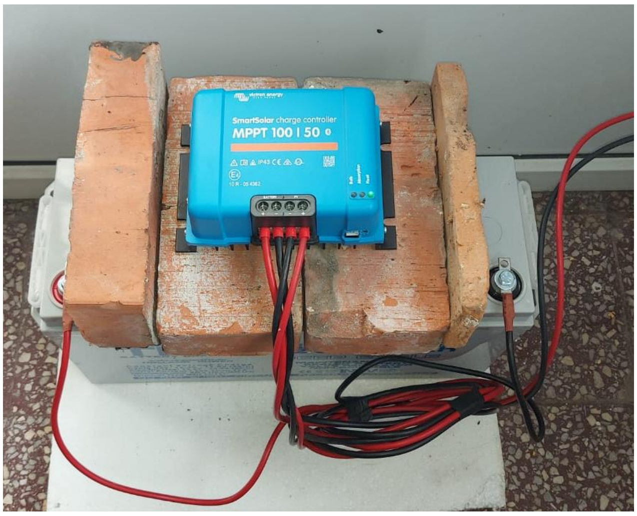

Fig. 11. MPPT charge controller

4. CS – solar system monitor – Victron app;
5. CM – electromechanic actuation command system, using a Controlino type PLC controller;
6. BR – metallic excavator arm – welded structure made out of S235 carbon steel (fig. 12);

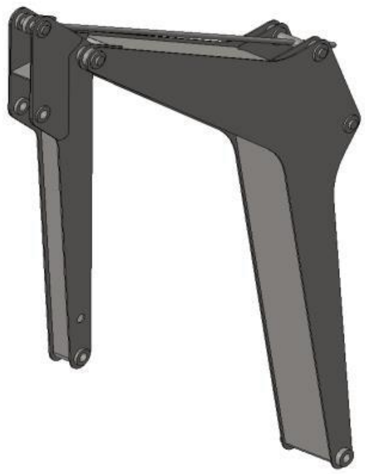

Fig. 12. Metallic excavator arm

7. M – actuator functionality monitoring system. This is composed of and Arduino Mega controller which collects and stores the data generated by a rotative encoder mounted on the mechanical joint of the excavator arm, by a linear encoder mounted on the electromechanic actuator and by a force transducer;
8. DM – force transducer with a capacity of 1000kg (fig. 13);

Fig. 13. Force transducer

9. AC – electromechanic actuator, with an optimum operating voltage of 12 V (fig.14);

Fig. 14. Electromechanic actuator

10. SM – metallic structural base – welded out of S235 carbon steel (fig. 15).

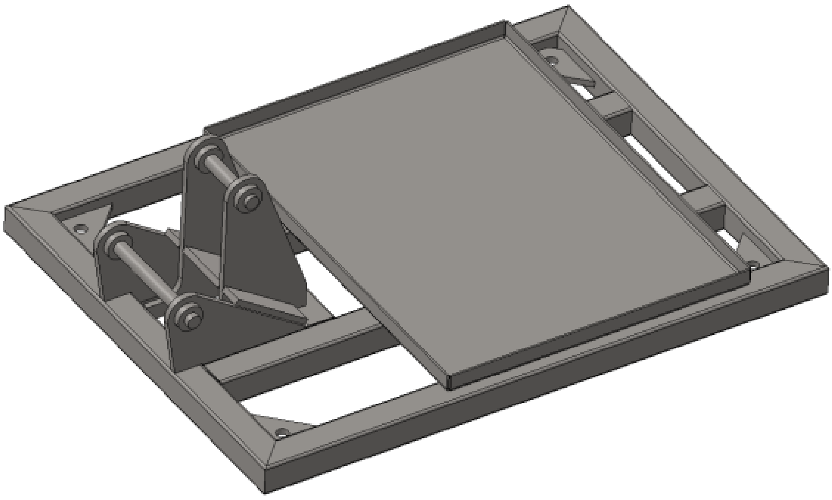

Fig. 15. Metallic structural base

The proposed solution does not necessarily imply the mounting of the solar panels directly on the construction equipment. The experimental stand could also be adapted into a stationary charging station.

The originality of the project stems from the use of green energy sources in the field of construction machinery with the intent of reducing fossil fuel and noise pollution, thus having a positive impact on the quality of life on a construction site and in nearby environments. There is a current demand for reduced pollution in urban construction sites. Real-estate developers are stimulated, from the very first stages of a construction project, to use alternative energy sources, such as solar panel arrays mounted in construction sites during initial organizational stages of a project.

This way, there is a source of alternative green energy on site, which can be used for the powering of construction equipment. The aim of the proposed project is to obtain an algorithm for the balance between the consumption of energy by construction equipment and the amount of energy stored in the electric accumulators.

The optimisation of the actuation system for an excavator arm fuelled by solar panel energy can be performed using an experimental model built for this purpose. The actuator must be driven in such a way that peak loads are as low as possible, while also taking into account the capacity and other performance characteristics of the electric accumulators.

In the case of a large number of very short, high peak electrical spikes, the batteries will undergo a rapid deterioration, which leads to premature discharge events. In order to limit the occurence of such phenomena during digging operations, a damping sequence for the power spikes absorbed by the actuators must be developed. This sequence must be able to be peformed in parallel with the other activities in which the operator of the equipment is involved and independent of the operator’s control. Such a system could be succesfully implemented into predefined, automated digging programs offered by the construction equipment.

For the actuation system of the experimental model’s excavator arm, various actuation sequences will have to be developed, which take real digging regimes into account and which feature the proper damping algorithms for peak loads. The first step to achieve this goal is to pergorm a SolidWorks simulation in which various digging sequences are tested. These sequences will then be later evaluated and validated by comparing theirs actual physical results obtained from the experimental stand. The SolidWorks simulation is presented in fig. 16.

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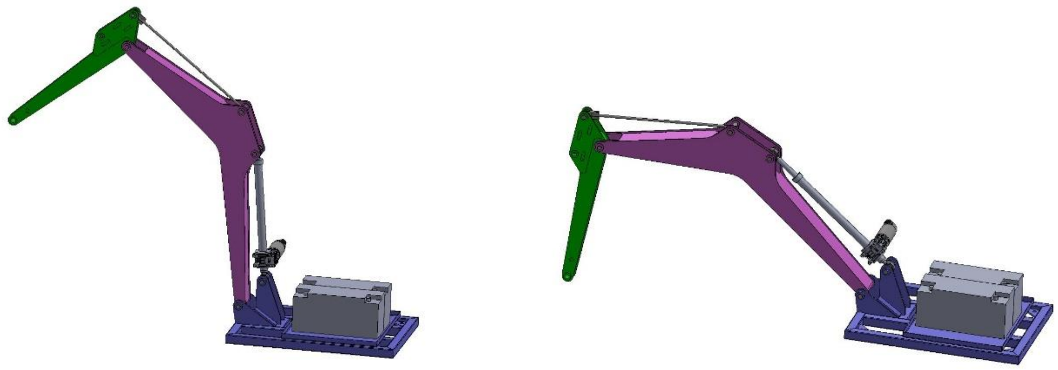

Fig. 16. SW simulation of the functionality of an actuation system for the arm of an excavator

Using SolidWorks Motion Analysis [12], the system was tested in a virtual environment, where several work scenarios were created. The following were taken into consideration:

- Different loads on the excavator's bucket an on the excavator's arm, which is driven by the electromechanic actuator;
- Different positions of the boom arm relative to the stick arm during digging operations;
- Various digging programs – in terms of velocities and accelerations applied at electromehcanical actuator level.

One possible scenario has been thus defined:
Following completion of the simulation we have obtained the following trajectory of the boom arm joint and the required force to properly acutate the arm (fig. 17).

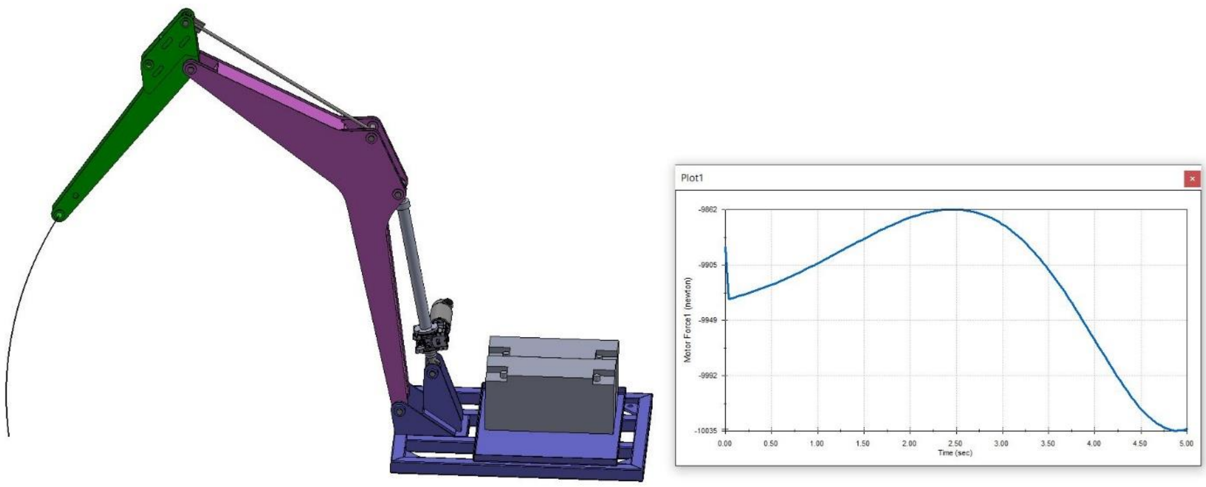

Fig. 17. Trajectory of the boom arm's joint

With the help of the simulation produced by SW Motion Analysis, the necessary power required to drive the electromechanic actuator has been estimated, together with the required energy which the actuator must draw from the batteries. Multiple iterations of the simulation were run, with various values for the load on the boom arm's final mechanical joint, as well as for the velocity and acceleration at the excavator arm level, which resulted in the simulation of real-life work scenarios (fig. 18). In figure 19 are presented the results of a simulation where 1000 N of force were applied to the final joint of the excavator arm. The model's own weight was also taken into account, which resulted in a 45 mm displacement at the actuator rod's level, the excavator arm being raised for a duration of 2 seconds, then lowered back to initial position in another 2 seconds, followed by yet another 5 mm raise of the arm in one second.

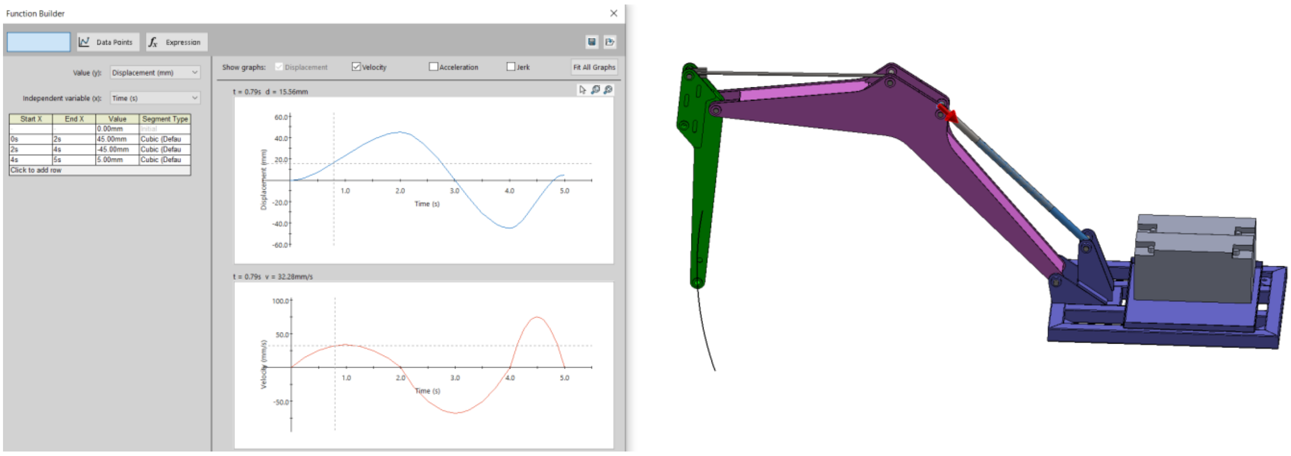

Fig. 18. Scenario for the electromechanical actuation of the excavator arm model

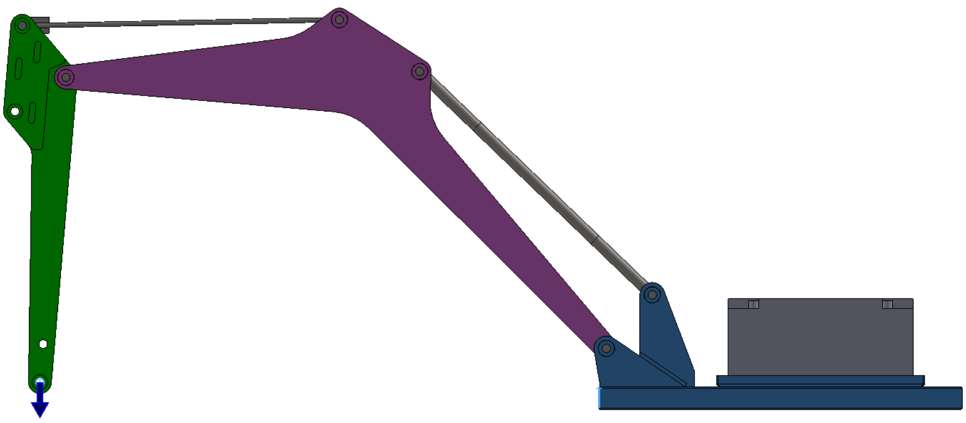

Fig. 19. 1000 N load applied to the final joint of the excavator arm

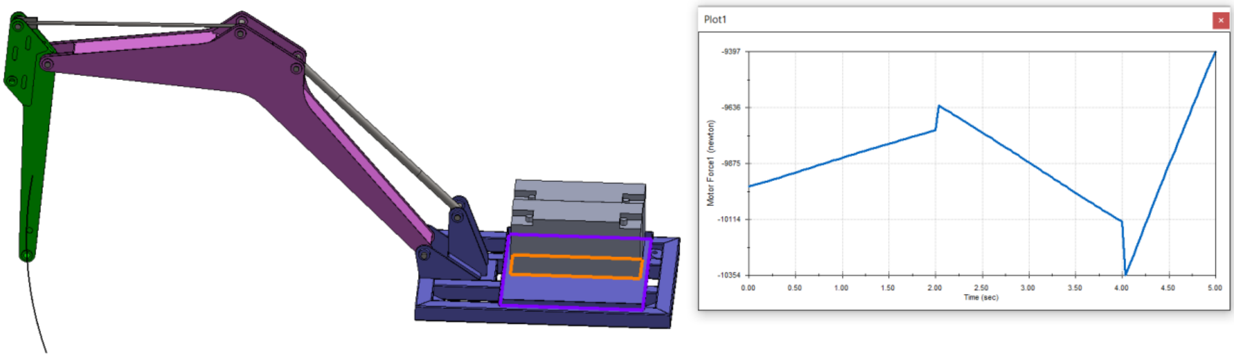

Fig. 20. Power at the electromechanic actuator level and the variation of the angle between arm and base

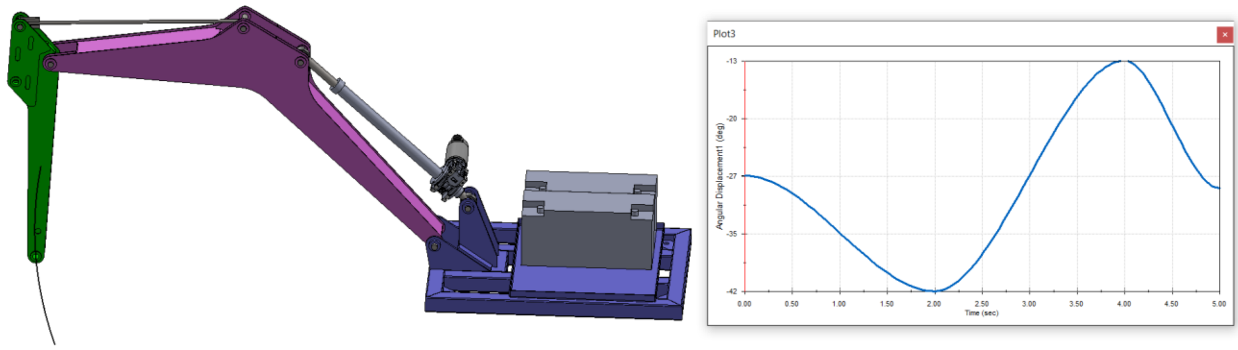

Fig. 20. (continued) Power at the electromechanic actuator level and the variation of the angle between arm and base

Following the simulation, the maximum necessary force for driving the electromechanic actuator has been calculated at 10354 N and power spikes have been detected during the simulation run (fig. 20) which must be optimised in the case of using photovoltaic panels and battery packs to power such an actuator. These power spike are present and detected even during fairly simple work scenarios. Simulations run for much more complex work sequences have determined the necessity of optimizing the functionality of the electromechanic actuator.
The optimisation will be performed through an actuation sequence which will be obtained by corellating results obtained from the simulation with future results obatined through experimental means.

3. Conclusion

Based on the performed research, the ever-increasing interest in electrical actuation solutions for construction machinery can be confirmed. The use of such equipment is well suited for urban areas and enclosed spaces where internal combustion engines can't be used due to polluting emissions. Such methods of actuation would also prove very welcome in the fields of food industry, agriculture and interior spaces of public buildings where the rupture of a hydraulic system component could cause oil contamination of aforementioned spaces. Various technological advances are currently being made in terms of development of electromehcanic actuation solutions for construction equipment. Electric actuation for such pieces of machinery is also being taken into consideration for far future applications, such as digging in low temperature vaccum environments, like space or exoplanets.
In order to validate the possibility of using an electromechanical actuation system, a series if simulations have been performed in a virtual environment. Following these simulations, load spikes were detected, which must be dampened when using our proposed solution for energy production and storage. In order to properly use solar panels to produce green energy and store said energy in rechargeable battery packs, some type of load spike correction must be implemented in the command and control module of the actuation system. In this way, the equipment will function properly, corecting the load spikes, independent of the commands issued by the operator. Corrections will be performed based on the position of the excavator arm and the measure load on the excavator bucket.

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