Constructive solution of battery swapping unit in service station for unmanned agricultural robot

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Abstract. The fully automated battery swapping unit is an essential part of unmanned agricultural robot service, ensuring the continuous operation of the robot by allowing the agricultural vehicle to replace its depleted battery with a fully charged one without human intervention, enabling it to continue its work cycle in the field. Thus, the battery swapping unit is part of service station systems, along with fertilizer filling, water supply, energy generation, and storage systems. This article describes a unique prototype of a battery swapping unit that safely replaces a depleted battery with a fully charged one in 223.5 seconds. The main role is played by the moving battery cart, which transports the battery between the charging and robot positions using a gripper equipped with an electric lock, attached to the actuator, and a V-belt transmission driven by an electric motor. The selection of the optimal rotation frequency of the motor is also discussed in this article.

Key words: battery, battery swapping unit, battery charging unit, unmanned agricultural robot, service station, energy supply.

INTRODUCTION

The current interest in the electrification of agricultural vehicles is steadily growing as it provides a solid foundation for the design of autonomous vehicles, significantly increasing agricultural productivity and achieving sustainable food production. However, the primary challenge is the demand for a more powerful energy source, combined with the low energy density and limited lifespan of batteries - a problem that could theoretically be addressed by installing larger batteries, though this approach is often difficult and costly. To avoid this, a solution is needed to exchange batteries directly in the field. Such a solution is provided by a mobile service station equipped with a battery swapping and charging unit.

Looking back in history, manual battery replacement services were first offered in the early 1900s to overcome the limited range of electric vehicles. This solution was popular until the mid-1920s (Mahoor et al., 2017). Much later, in 2007, Better Place was founded, offering the first commercial automatic battery exchange service, but it was only available for electric vehicles. For example, the technology for swapping batteries of electric buses was first introduced in China in 2008. During the Summer Olympics,

batteries were swapped on about 50 buses operating on various routes. Since then, battery swapping for different vehicles has been widely practiced in China, Japan, and South Korea (Nio, 2020; Qi et al., 2020).

In 2014, the Chinese company NIO began promoting battery swapping technology (NIO Power Grid technology). It offers a combination of multiple energy charging solutions focused on improving user experience. The core of this strategy is NIO's paid, interchangeable, and upgradable smart energy system. The company announced that by October 5, 2020, the total number of battery exchange services for electric vehicles in China had reached 1 million - twice as many as on May 25, 2020. This demonstrates the rapidly growing demand for this service. Between spring 2020 and spring 2021, NIO has increased the number of its battery swapping stations from 131 to 155 (Nio, 2020; Qi et al., 2020).

Most existing agricultural machinery uses fuel-powered engines as its energy source. In the current context of aiming for zero emissions and carbon neutrality, agricultural vehicles with reduced fossil fuel usage are being developed to mitigate environmental impact (Yamasaki & Noguchi, 2022). Robotic electric vehicles (EVs) have been used in agriculture as harvesting robots for years (Hayashi et al., 2010), and with recent advancements in battery technology, the use of electric robots in outdoor conditions has become more frequent. Agricultural robots not only provide an opportunity to strengthen agricultural food systems by addressing labour shortages but also offer the potential to reduce CO_2 emissions (Gonzalez-de-Soto et al., 2015) and soil compaction (King, 2017; Duckett et al., 2018).

Currently, 6.4% of the world's economic productivity comes from agriculture, and in many countries, agriculture is a vital economic sector. In addition to feeding billions of people, agriculture provides jobs for a large portion of the world's population. Concerns about food security, rapid global population growth, and unpredictable climate change have prompted the agricultural industry to seek new and efficient ways to increase crop production. As a result of these efforts, wheeled mobile robots are gradually becoming more widespread in this sector as part of an ongoing technological revolution (Bai et al., 2023; Dziekański & Kochanowski, 2023; Ibrahim & Truby, 2023; Rai et al., 2023; Ryan et al., 2023; Vásconez et al., 2023; Wang et al., 2023).

If we consider the challenges of electric vehicles, including agricultural robots, the most critical component of any electric vehicle is the battery, as it determines the vehicle's performance in all aspects. Parameters affecting the battery's lifespan include the state of charge (SOC), temperature, and current. High-power lithium-ion batteries are commercially available components with specified power, performance, and lifespan. Lithium-ion batteries are prevalent in most electric vehicles due to their long lifespan, high voltage, fast charging capability, and high energy density (Revankar et al., 2021). However, the charging of electric vehicle batteries plays a crucial role in their adaptability. The current charging process typically involves connecting the electric vehicle to a household socket or charging station and linking it to the power grid for several hours. This method takes much longer than refuelling an internal combustion engine vehicle and is a significant obstacle to the popularization of electric vehicles. An exception is ultra-fast high-power charging stations (up to 350 kW), which can charge an electric vehicle depending on the battery capacity in approximately 20 minutes. However, rapid charging of many electric vehicles may negatively impact the battery's energy quality parameters (Chudy & Mazurek, 2019; Chudy & Stryczewska, 2020).

One effective solution to address the challenges associated with charging electric vehicles is the use of battery swapping stations (BSS), which allow depleted batteries to be exchanged for fully charged ones. Unlike traditional wired or wireless charging methods, which can take a significant amount of time, battery swapping can be completed in just a few minutes. Thanks to BSS, electric vehicles can extend their range and reduce the time needed for further travel (Wu et al., 2020), which would otherwise have been spent charging the battery at a charging station.

The following are various methods of battery swapping, categorized based on the battery's position within the vehicle and, for example, the location of the manipulator responsible for exchanging the battery (Adegbohun et al., 2019; Ahmad et al., 2020):

• Bottom swap: Designed for vehicles with a battery located at the bottom of the vehicle. The battery swap station is configured so that the vehicle is placed on a raised platform, and the battery is swapped from below using a manipulator and other accessories typically located below ground level.

• Top swap: Common in electric buses, where the batteries are located under the roof. When the bus arrives, the roof opens to allow battery swapping using a manipulator.

• Side swap: Typically used in vehicles with batteries mounted on the side.

• Rear swap: Common in vehicles with the battery mounted at the rear. This method is usually employed in vehicles with large trunks.

• Front swap: Suitable for agricultural vehicles, as most of their working equipment is located at the rear, while the battery is positioned at the front. This method is used in the agricultural robot featured in this project (Virro et al., 2020).

This article provides an overview of front-positioned battery swapping, as agricultural machinery typically has working implements located at the rear, making it practical to install the battery container at the front of the vehicle.

Battery swapping stations (BSS) can operate successfully only when there is continuous communication between the various components of the system: the vehicle, the BSS, and the information exchange system. The information exchange system facilitates communication between vehicles and the station (Ahmad et al., 2020). Four different states are considered for each battery: charging required, charging, fully charged, and electric vehicle (EV) battery out-of-station (Fig. 1).
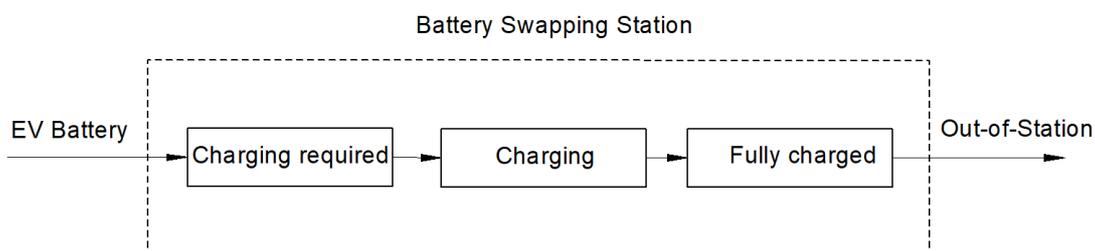

Figure 1. Battery state diagram.

Well-known battery swap systems are mostly integrated designs where the entire electric swapping cart mechanism is placed underground (Patent DE4229687, 1994). However, these systems have several drawbacks: such an automatic battery swapping station cannot be relocated, involves high construction costs, is inconvenient to maintain,

is usually used indoors, does not perform well in adverse outdoor weather conditions, and therefore has limited applications.

The articles Liu et al. (2018) and Toksoz et al. (2011) describe battery swapping and charging stations for aerial drones. Their uniqueness and drawback lie in the fact that they require the use of many batteries, as the flight time of a drone with a fully charged battery is only about 15 minutes.

According to patent US20170259675, a well-known system is simple and safe, offering an autonomous battery swapping solution for electric vehicles. It consists of various small, lightweight, and easily installable components that are convenient to transport (Patent US20170259675, 2017). In this solution, an electric transfer cart is positioned on a guide rail and moves back and forth along the track to complete the battery transfer between the vehicle and the battery swapping unit. Additionally, the automated battery swapping system includes a control module to coordinate and manage the operation of each component within the system.

The electric transfer cart mechanism also incorporates a feature that can be raised and lowered vertically to align it with the vehicle's battery for swapping. However, the main drawbacks of such battery swapping systems are apparent: storing and moving batteries with large masses is complex, and the number of replaceable batteries required is significant. Moreover, the system is bulky because it is necessary to raise the vehicle to a working height to remove the battery from underneath.

The article discussing the battery swapping unit for electric vehicles (Adegbohun et al., 2019) describes an automatic battery swapping device where the electric vehicle is lifted by a lifting mechanism. The battery is then removed from the vehicle using a specialized lifting and transport device, transferred to a cabinet with multiple charging sockets, and replaced with a fully charged battery that the same device installs back into the vehicle.

The speed of battery swapping with this device is reduced due to the need to lift the vehicle, and the lifting mechanism makes the system bulky and complex. Additionally, the use of multiple battery packs is impractical when dealing with fewer than three batteries. It should be noted that this is a stationary battery swapping system, making it unsuitable for servicing agricultural robots, as it lacks the mobility required to support robots directly in the field.

Geely provides battery swapping technology for cement mixers and semi-trailer trucks. In these vehicles, the batteries are positioned behind the passenger cabins and are accessible from the top. In the BSS, a crane located above the vehicle lowers, lifts the battery, and transports it to the storage area, where a fully charged battery is ready. The entire swapping process takes five minutes. Geely's BSS occupies 19 m² of space, is equipped with solar panels, and can serve up to 50 vehicles daily (Zhejiang Geely Holding Group Co.). Similar to the previous system, it is a stationary battery swapping unit, and lifting the battery from the top is impractical for agricultural electric vehicles.

The utility model patent UA141092 U (2020) proposes the following method for battery swapping: the vehicle's battery is accessed from the side, eliminating the need to raise the vehicle to a working height or require the driver to exit. However, this approach requires electric vehicles to be equipped with universal batteries and compatible mounting mechanisms.

This system is similar to ours in that both rely on guides to transfer the battery and do not require lifting the vehicle for battery removal. In this system, a conveyor is used to move the batteries, taking the depleted battery for charging on one side and bringing the fully charged battery to the vehicle on the other. A robotic machine is intended for disconnecting and reconnecting the battery.

The battery swapping unit described in this article features a simpler design than the utility model mentioned earlier, as it does not require the use of a robotic machine.

There is also the possibility of wireless charging, as described in patent RU2757400 C1 (2021), and in the article Zhang et al. (2013). Wireless charging is an effective way to charge batteries; however, it requires the use of special antennas, which must be very bulky when handling high charging currents. Due to size restrictions on the robot's dimensions, this method cannot be used in this project.

Battery swapping, a novel solution for minimizing vehicle downtime, differs greatly in terms of readiness. While some systems are commercially available, others remain in the demonstration stage. The scalability of this technology is vital, as it holds the potential to drastically reduce charging times (Piedel et al., 2024).

The most important aspects of the developed battery swapping system are as follows:

- Monitoring for the need to refill technological materials (e.g., fertilizer) or detecting a low battery charge level.
- Moving the robot to the service station.
- The robot's arrival at the service station platform and its positioning.
- Precise alignment and fixation of the robot to the battery swapping unit.
- Removing the battery container from the robot using a linear drive and placing it in the charging position.
- Gripping, moving, and installing the fully charged battery container into the robot.
- Releasing the locking elements, allowing the robot to leave the service station.

Efforts to develop innovative battery swapping units tailored to the needs of agricultural machinery are ongoing, with the goal of improving productivity, reducing downtime, and contributing to sustainable agriculture. Minimizing downtime is particularly crucial in agricultural operations, where uninterrupted performance is essential to maximize efficiency and maintain productivity. As highlighted by Mammarella et al. (2022), cooperative frameworks for unmanned systems emphasize the importance of seamless integration and operational continuity in field conditions, which aligns with the objectives of autonomous battery swapping systems. While various battery swapping systems have been proposed, each with its own advantages and limitations, a practical solution for agricultural machinery must address challenges such as mobility, ease of maintenance, and efficient battery swapping. It should be versatile enough to operate effectively in outdoor environments, capable of withstanding diverse weather conditions, while also remaining cost-effective and user-friendly.

During the preliminary research and development phase, it became clear that there are currently no technical solutions worldwide for the autonomous swapping of batteries in agricultural robots. Solutions designed for drones or cars are unsuitable for our agricultural robot and service station due to their structural specificities.

When comparing the battery swapping solution proposed in this article with previously mentioned alternatives, the advantages of the described device are as follows:

1. Front swap: This device provides an effective solution for swapping batteries in agricultural machines where the working tools are located at the rear of the vehicle, and the battery is positioned at the front (Virro et al., 2020).

2. Compact dimensions: The device does not require lifting the vehicle or battery during the swapping operation and includes only two charging positions, minimizing its overall size.

3. Short battery transport path: All movements occur on a horizontal plane, significantly reducing the transport path of the battery between the vehicle and the charging position.

4. Minimal number of moving components: By eliminating the need to lift the battery or the vehicle vertically, the device simplifies its mechanical design.

This article focuses on describing the prototype of an original battery swapping unit and optimizing the rotation frequency of the stepper motor used in the unit's belt drive. The stepper motor's rotation frequency directly influences the movement time of the battery cart and, consequently, the duration of the battery swapping cycle. The swapping cycle must be sufficiently short to ensure that the process does not cause additional downtime during robot servicing at the maintenance station, where tasks such as refilling the fertilizer hopper or spray tank are performed.

MATERIAL AND METHODS

The development activities of the agricultural robot's battery swapping unit included the compilation of requirements for the device, followed by patent research and determination of the technical level. Subsequently, the basic and detailed functions were defined, solution principles were selected, and from among them, a specific technical solution was chosen. A draft project was prepared along with a 3D model (Fig. 3), and a prototype was built (Fig. 6). After this, since one of the goals of the study was to optimize the operating time of the system, further work was carried out in the article to select the optimal rotation frequency of the electric motor, which controls the speed of movement of the trolley through a belt drive.

Fig. 2 shows the schematic diagram of the battery swapping unit (BSU), illustrating its components and their communication. The battery swapping unit is located on the platform of a mobile service station, where the undercarriage guides of the agricultural robot are attached to the floor (Fig. 3). These guides serve to initially orient and position the wheels of the agricultural robot relative to the battery swapping unit when the robot approaches the service station from the field for docking. For further precise alignment, conical guides (pos. 9) and locking elements (pos. 10, similar to pos. 3) are installed on the frame of the battery swapping unit. Their purpose is to secure the robot in a specific position during servicing.

The locking elements (hereinafter referred to as locks) are electrically operated and disengage when the robot is ready to leave the service station. The robot's batteries are housed in moisture- and dust-resistant containers (4), of which there are two: one located in the charging position of the battery swapping unit and the other mounted on the frame (6) attached to the agricultural robot.
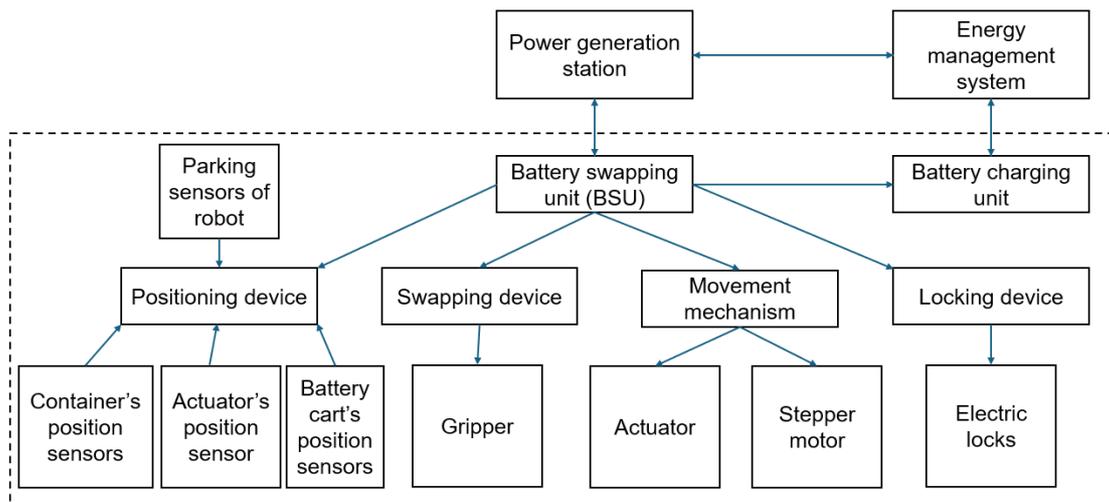
Figure 2. Schematic diagram of the battery swapping unit (BSU) for an agricultural robot.
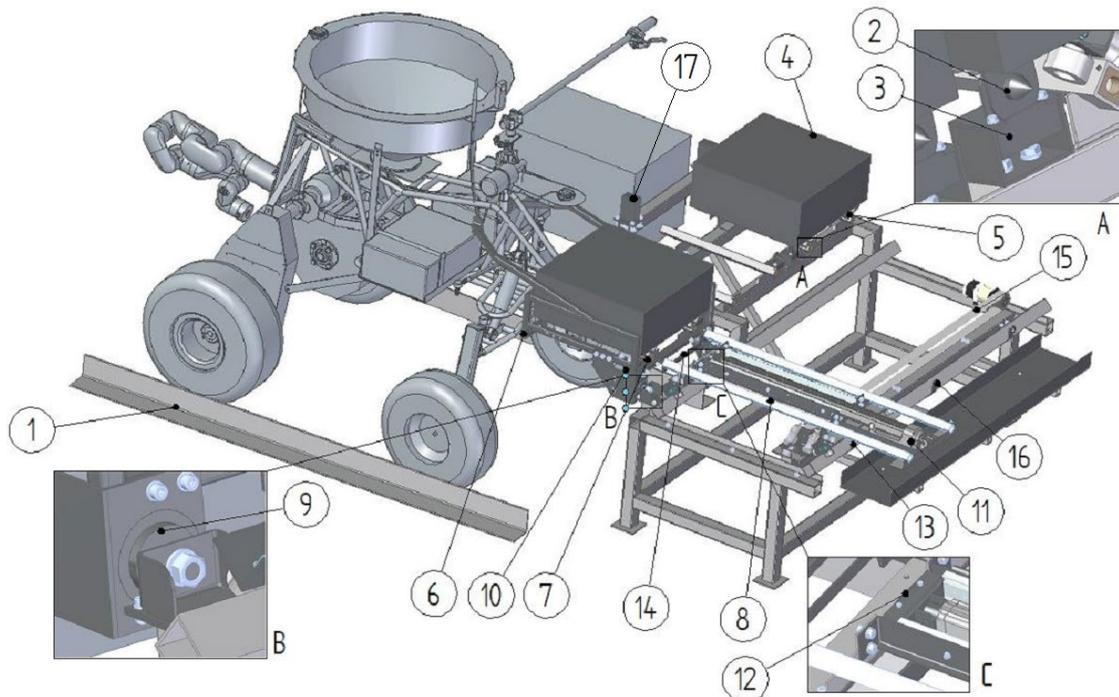

Figure 3. Model of the battery swapping unit with the agricultural robot docked to it: 1 – directional guide for robot wheels; 2 – conical pin-catcher; 3 – locking element; 4 – battery container; 5 – roller of the battery container; 6 – frame carrying the battery container on the robot; 7 – longitudinal guide; 8 – battery cart; 9 – conical guide on the frame of the battery swapping unit; 10 – locking element; 11 – linear actuator; 12 – gripper; 13 – sensor determining the zero position of the battery cart; 14 – plate equipped with catches; 15 – belt transmission equipped with a stepper motor reducer and pulleys; 16 – sensor registering the position of the battery cart; 17 – sensor of the battery container's state.

To facilitate smooth movement, each battery container (4) is equipped with eight rollers (5) attached to its bottom, allowing it to move seamlessly between the robot, the battery cart, and the charging position. The frame (6) carrying the battery container on the robot is equipped with rectangular-profile longitudinal guides (7), on which the battery container moves during the swapping process. Similarly, rectangular-profile guides are present on the battery cart (8), enabling the battery container to roll between the robot and the cart.

To prevent vertical movement of the battery container, the frame (6) carrying it is fitted with conical pins (2) that act as catchers, slotting into openings on the fixation plates of the battery container. Horizontal movement of the battery container (4) is restricted by locks (3) located on the frame (6), working in tandem with two fixation plates attached to the battery container. These locks secure the container's position and only disengage upon receiving an electrical signal.

Precise positioning and docking of the robot with the battery swapping unit frame are achieved using conical catch pins (9) located at the front of the unit. These pins fit into recesses on inverted conical elements on the robot frame, ensuring tight contact and secure docking. Once positioned, parking sensors mounted on the swapping unit frame send a signal to the control module, initiating the swapping process.

A linear actuator (11) mounted on the battery cart and movable longitudinally is then activated. At the end of the actuator's rod, a gripper (12) equipped with a locking mechanism, guided by linear guides, grips the battery container (4) via an element attached to its bottom. The gripper (12) transfers the container from the robot's frame to the battery cart (8). Subsequently, the battery container (4) is moved to one of the charging positions (CP_1 or CP_2, Fig. 3).

The zero position of the battery cart (8) on the battery swapping unit is determined by an optical sensor (13). Additional optical sensors (16) are located at charging positions CP_1 and CP_2 (designated as sensors B1 and B2, Fig. 4) to confirm the presence of the battery container in the charging position.

The working principle of battery swapping is as follows: after successful docking with the battery swapping unit, the parking sensors provide information to the control module that the agricultural robot is now in the correct position, triggering the control program. This program activates linear actuator (11) and the gripper (12), initiating its movement from the 'zero point' towards the agricultural robot's battery container. Subsequently, the release of the springs holding plate (14) equipped with conical pins occurs, allowing the plate (14) to move forward directly, with its pins docking into the bushings on the agricultural robot's battery frame. These pins fix the position of the battery cart (8) and ensure stable linear movement of the battery container (4) between the robot and the battery cart (8). Once battery cart (8) is docked with the robot, the gripper (12) of the actuator (11) continues its movement until it grasps the plate attached to the bottom of the battery container (4). Locks (3) holding the battery container (4) release, and the gripper (12) grasps the container, initiating its reverse movement under the influence of the linear actuator (11). The battery container (4) moves from the frame of the robot's battery container to the battery cart (8) to the so-called 'zero point'. During this return movement, the conical pins of plate (14) are withdrawn from the bushings by the plate (14) attached to the gripper of the actuator (12), pushing the plate (14) with the pins back. When the battery container (4) reaches the 'zero point', the belt transmission

(15) driven by a stepper motor and equipped with the pulley on the end of its shaft, activates, causing the battery cart (8) with the battery container (4) to move transversely to the direction of the actuator's movement towards the free charging position (CP_1 or CP_2, Fig. 4) until it reaches point D or F (Fig. 4), where the battery cart (8) stops at a pre-programmed position. The accuracy of this position is verified by the optical sensors (16) mounted on the frame of the battery swapping unit. The battery container (4) is then moved by actuator (11) to its charging position.
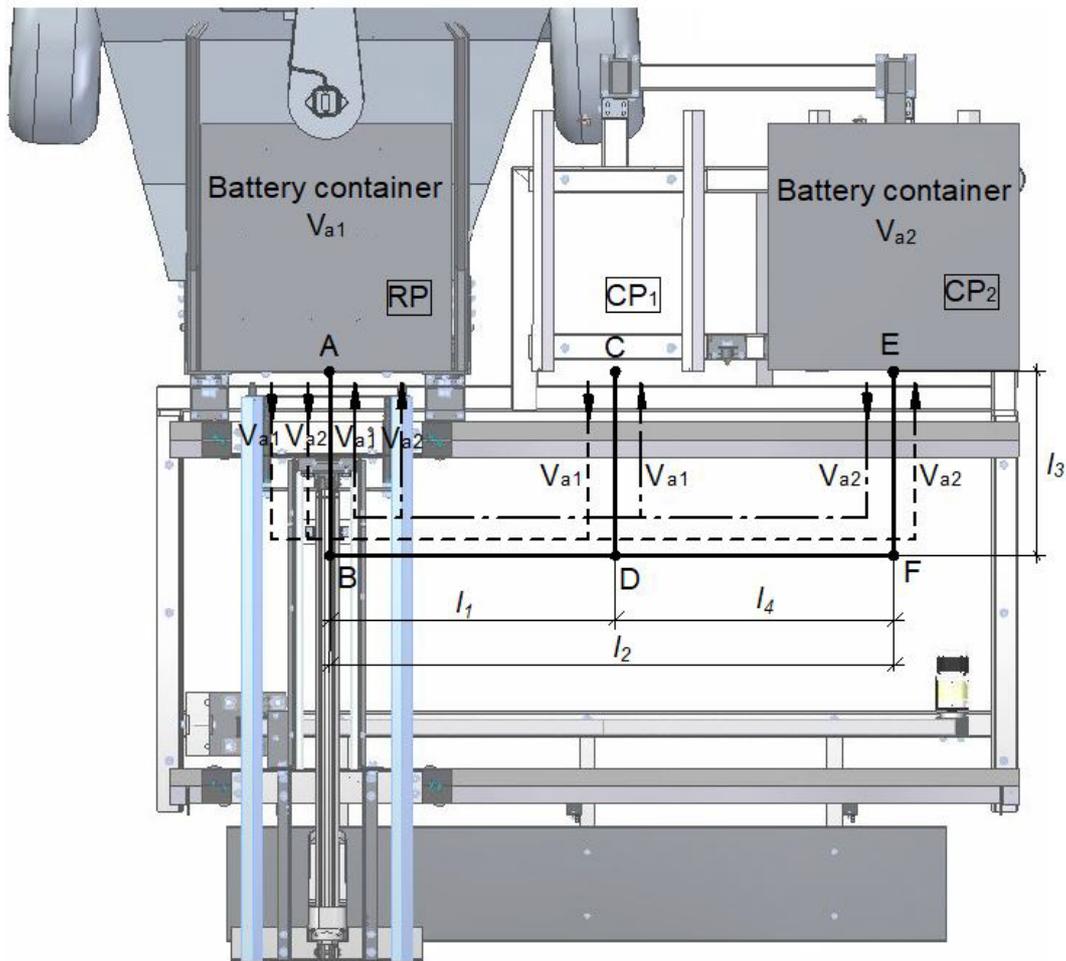

Figure 4. Layout and movement scheme of battery containers: A, B, C, D, E, F – points on the kinematic scheme; arrows indicate the direction of movement of the first V_{a1} and the second V_{a2} battery container; dashed lines represent the path from the robot position to the charging position, and dash-dotted lines represent the path from the charging position to the robot position; l_1, l_2, l_3, l_4 – segments of the battery container's movement path; CP_1 and CP_2 – the first and second charging positions respectively; RP – the initial position of battery container in the robot.

Upon reaching the charging position, the end position sensor O_1 (Fig. 5) sends a signal to the control module indicating that battery container (4) has reached the correct position, and the movement of the gripper (12) of the actuator immediately stops. The movement of actuator (11) is also programmatically limited, and sensor (17) ensures that the gripper (12) does not move further if a signal from sensor O_1 (Fig. 5) is not received

for any reason. The battery container (4) with the battery inside is now in its charging position and is connected to the charging platform socket via its plug. Subsequently, battery parameters are tested, and the charging process begins. Immediately after the battery that requires charging is brought to its charging position CP_1 or CP_2 (Fig. 4), the electrical lock of the gripper (12) opens, releasing the battery container (4). Lock (3) on the frame of the charging position is closed, preventing any movement of battery container (4) in this position. The released linear actuator gripper (12) starts its return movement until it reaches its initial position. From this moment, the empty battery cart (8) moves to the second charging position, reaching point D or F (Fig. 4). When reaching there, battery cart (8) stops, but the gripper (12), with the help of the linear actuator (11), starts its movement to pick up the fully charged battery. Another docking occurs, and then the fully charged battery in container (4) located in charging position CP_1 or CP_2 (Fig. 4) is grasped. Lock (3) blocking the movement of the battery container (4) opens, and the battery container (4) is then moved from the charging position to the battery cart (8). Upon returning to its initial position, the gripper (12) and the actuator (11) stops, and the battery cart (8) with the battery container (4) moves longitudinally to point B (Fig. 4), i.e., the 'zero point' opposite the docked robot. Upon reaching point B (Fig. 4), the battery cart (8) docks with the agricultural robot, the transverse movement of the battery container (4) from the battery cart (8) to the agricultural robot's battery frame (6) occurs, the position of the container (4) on the frame (6) is fixed with two electric locks (3) (2 pcs.), the lock on the gripper (12) is released, and the gripper (12) returns to its initial position. Simultaneously, battery cart (8) is disconnected from the robot.

Furthermore, once the robot is equipped with a fully charged battery and ready to return to the field, the two locking elements (10) that hold the robot in place are released. This disconnects the robot from the precise positioning mechanism of the battery swapping unit. At this point, the robot is prepared to leave the service station and resume its unfinished tasks in the field.

Fig. 4 illustrates the movement of the battery container during the battery swapping cycle. The diagram uses arrows and various line types to depict the directions of movement of the battery containers (hereafter referred to as batteries). The movement of batteries to the charging positions is represented by dashed lines, while their return from the charging positions to the robot is indicated by dash-dotted lines. The battery swapping cycle begins at position in point A, which corresponds to the battery's position within the robot RP, and concludes at points C or E, depending on the charging position (CP_1 or CP_2). There are two batteries in total, V_{a1} and V_{a2}, each assigned to one of the two charging positions (CP_1 or CP_2). If the battery Va1 in the robot requires charging, it follows the path from points A → B → D → C to reach charging position CP_1. Along this route, changes in the direction of movement occur at points B and D. Similarly, battery V_{a2} follows the path A → B → D → F → E to reach charging position CP_2, with direction changes occurring at points B and F.

Principles of selecting the drive for the battery swapping unit

According to the requirements set for the unit, the total cycle time for battery swapping, denoted as t_s, must not exceed the time required for other technological operations, such as filling the fertilizer hopper of the robot spreader or the tank of the

robot sprayer with a plant protection agent, denoted as t_t, which does not exceed 4 minutes. This relationship can be expressed as:

$$t_s \leq t_t, \tag{1}$$

The total cycle time for battery swapping t_s consists of three components:

$$t_s = t_a + t_p + t_l, \tag{2}$$

where t_a − the longitudinal movement time of the battery container, s; t_p − the transverse movement time of the battery cart, s; t_l − the time for operating the locks and relays of the unit, s.

The logic used to solve Eq. (3) is as follows: since an actuator is used to move the battery container longitudinally, and its movement speed v_l is practically constant, the time for its movement t_a can be calculated as:

$$t_a = \frac{l_3 \cdot k_r}{v_1} \cdot k_a, \tag{3}$$

where l_3 − the length of the battery cart movement path longitudinally, m (Fig. 4); k_r − the number of longitudinal movements during one operation cycle; v_1 − the movement speed of actuator, m min^{-1}; k_a − the number of longitudinal operations performed during one battery swapping cycle.

The selection of sufficient time for transverse movements of the battery cart t_p was based on the appropriate speed selection of the electric motor. The time for the transverse movement of the battery cart t_p can be calculated as:

$$t_p = \frac{k_g \cdot (l_1 + l_4)}{v_2}, \tag{4}$$

where $l_1 + l_4 = l_2$ is the length of the battery cart movement path transversely (Fig. 4); v_2 − the linear movement speed of the battery cart, m s^{-1}; k_g − the number of transverse movements during one working cycle.

The linear movement speed v_2 of the battery cart, resulting from the rotation frequency of the stepper motor shaft, is expressed as follows:

$$v_2 = \frac{n_g \cdot \pi \cdot d_g}{i}, \tag{5}$$

where n_g − rotation frequency of the stepper motor shaft, s^{-1}; d_g − diameter of the pulley, m; i − gear ratio of the reducer of motor ($i = 15{,}3$).

Substituting Eq. (5) into equation (4), we obtain the following equation for calculating the transverse movement time t_p of the battery cart:

$$t_p = \frac{k_g \cdot i \cdot (l_1 + l_4)}{n_g \cdot \pi \cdot d_g}, \tag{6}$$

The actual transverse movement time t_p of the battery cart may differ from the calculated value, because it does not consider the additional time required to accelerate and decelerate the battery cart carrying the container with batteries (total mass 72 kg) during movement. This time is planned to be evaluated during the initial tests. The time t_p depends on the stepper motor shaft rotation frequency n_g, and its impact on the total cycle time t_s of the battery swapping operation can be characterized by a coefficient λ as follows:

$$\lambda = \frac{t_p}{t_s} \cdot 100. \tag{7}$$

RESULTS AND DESCUSSION

Fig. 5 shows the schematic diagram of the automation of the battery swapping unit. The end position sensor O_1 of the gripper 12 (Fig. 3) ensures that the gripper 12, powered by the actuator 11, stops at the correct position. Sensors B_1 and B_2 monitor the end position of the battery container, determining whether it is in the charging position or not. If, for some reason, there is no signal from the O_1 sensor, these sensors stop the gripper 12 and send a signal to the control module.
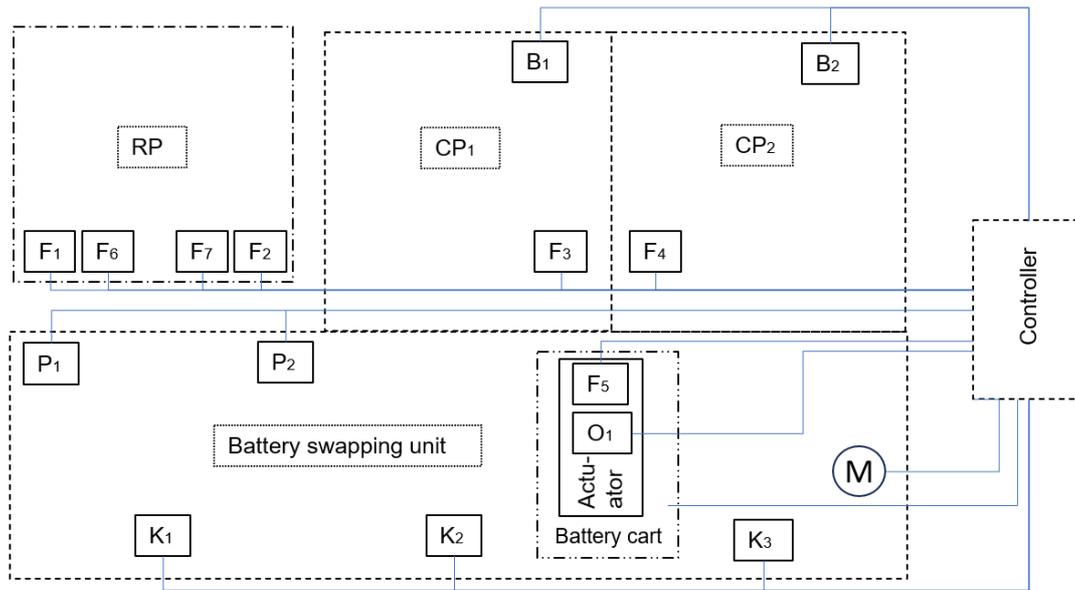

Figure 5. Schematic diagram of the battery swapping unit's automation: B_1 and B_2 – battery container position sensors; CP_1 – first charging position; CP_2 – second charging position; F_1 and F_2 – electric locks that hold the robot; F_3 and F_4, F_6 and F_7 – electric locks that hold the battery container; F_5 – electric lock on the actuator gripper; $K_1...K_3$ – battery cart position sensors; M – motor; O_1 – actuator end-position sensor; P_1 and P_2 – agricultural robot parking sensors; RP – robot position.

Sensors K_1, K_2, and K_3 are responsible for determining whether the battery cart is positioned correctly opposite the charging or robot positions. Locks F_1 through F_4 secure the battery container in the charging or robot position, preventing unwanted movements. Lock F_5 on the gripper ensures that the battery container is securely grasped. Locks F_6 and F_7 engage when the robot is in the parking position, keeping it attached to the battery swapping unit until the battery swapping cycle is complete. Parking sensors P_1 and P_2 determine whether the robot has been parked correctly or if its position requires adjustment. CP_1 and CP_2 are the charging positions for the battery containers, where CP_1 is used by battery container V_{a1}, and CP_2 is used by battery container V_{a2} (Fig. 4). Fig. 6 shows the specifications of the main electrical components of the battery swapping unit. The controller, based on the Arduino Nano Every core, manages the control and data exchange for the unit. It governs the operation of the actuator, motor, electric locks and sensors. During the development process, a prototype of the described battery swapping unit was built. This prototype is shown in Fig. 7, docked with the agricultural robot.
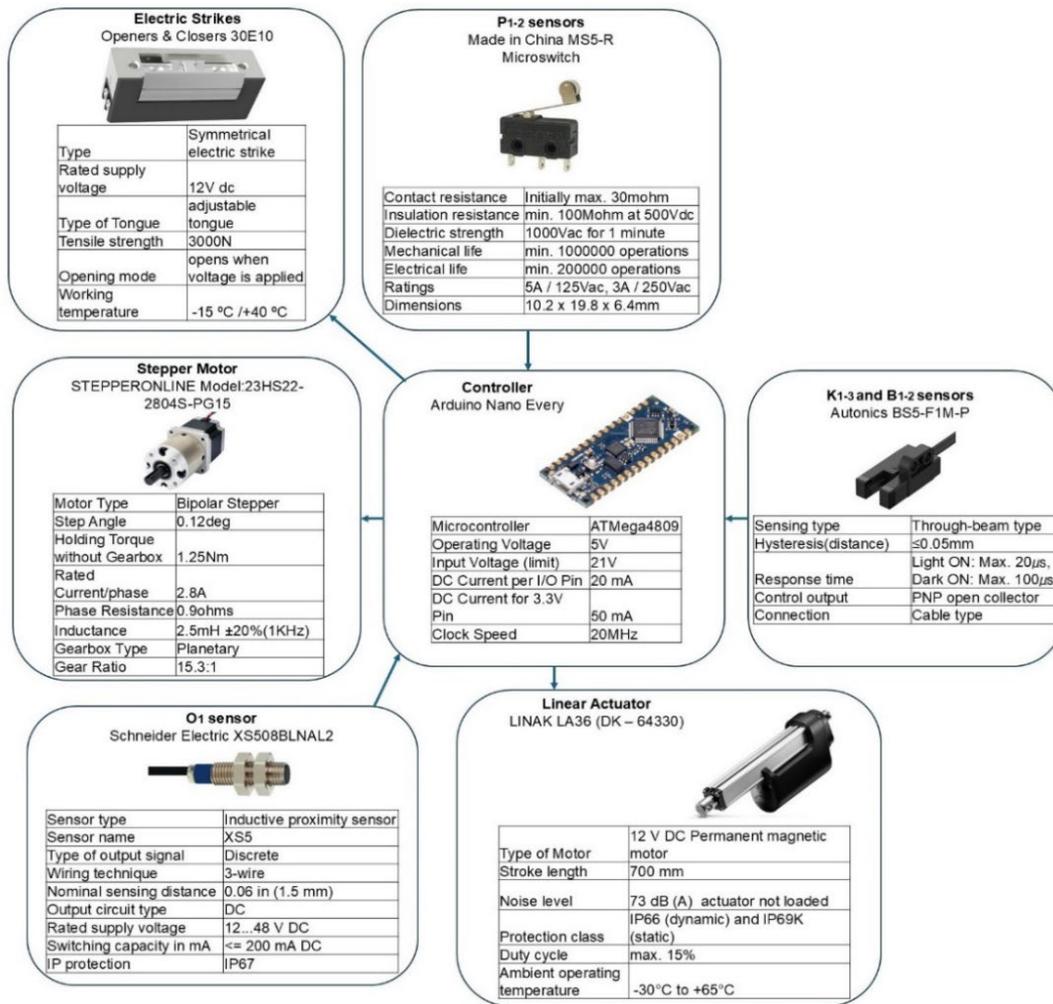
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Figure 6. Specification of the main components of control system of the battery swapping unit.

Fig. 8 illustrates the operational algorithm of the battery swapping unit. The cycle begins with the successful docking of the agricultural robot with the battery swapping unit and concludes with the reinstallation of the fully charged battery into the robot, the release of the locking mechanisms securing the robot's position, and the robot's readiness to return to the field to resume its tasks.

Figure 7. Prototype of the developed battery swapping unit docked with the agricultural robot: 1 – battery swapping unit; 2 – agricultural robot; 3 – battery containers.
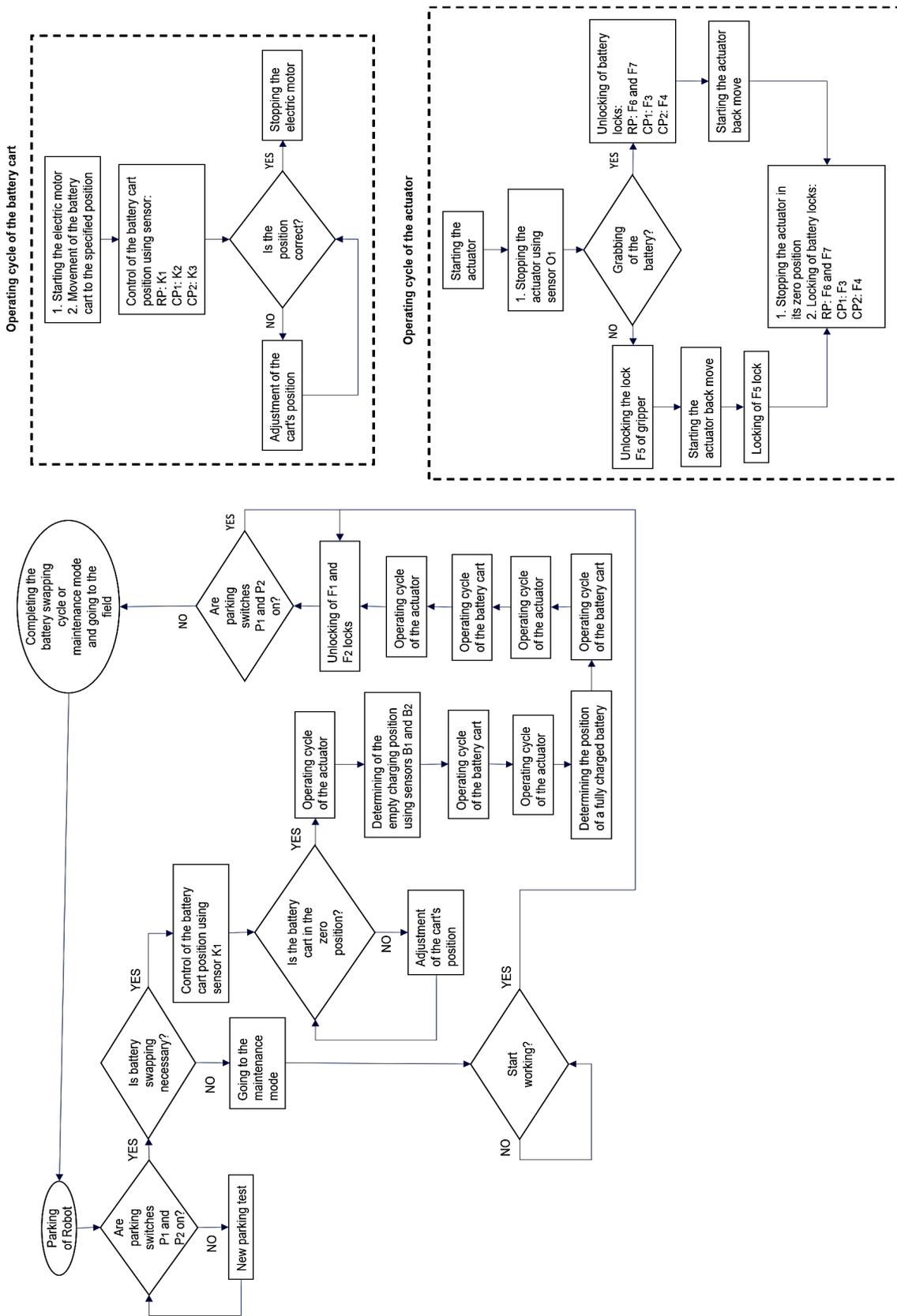
427

Figure 8. Operating algorithm of the battery swapping unit.

The back-and-forth or longitudinal movement of the battery cart should be considered as a working stroke, i.e. if there are two movements, i.e. $k_r = 2$, then the length of one working stroke is $l_3 \cdot k_r = l_3 \cdot 2$. If $l_3 = 0.65$ m, $v_l = 1.57$ m min^{-1} and $k_a = 4$, then the time of longitudinal movement of the battery container $t_a = 3.312$ min or 199.5 s. Taking into account that $k_g = 2$; $i = 15.3$; $l_1 + l_4 = 1.13$ m; $d_g = 0.063$ m, and the suitable rotation frequency of the stepper motor shaft is sought within the range $n_g = 5...20$ s^{-1}, then the time t_p of the transverse movement of battery cart according to equation (6) is in the range $t_p = 8.7...35$ s.

Since the performance of the battery swapping unit depends on the optimal functioning of its stepper motor, determining the optimal rotation speed can improve the efficiency and reliability of the device, ensuring smooth operation under real agricultural conditions.

Based on the design requirements discussed earlier, the selection of the optimal rotation frequency of the stepper motor, which is one of the key elements of the battery swapping unit, is analysed below.

From the conducted test, it is evident that the stable operation of the drive motor and belt transmission of the battery cart is ensured up to a rotation frequency of the stepper motor shaft of $n_g = 68.6$ min^{-1}. Rotation frequencies higher than this value cause sudden accelerations that overload the motor (with a power of 48 W) and lead to step losses in the stepper motor, which in turn affects the positioning accuracy of the battery cart. Analysing the trend in Fig. 9, it can be seen that a higher rotation frequency n_g does not lead to a significant reduction of the battery swapping cycle time t_s. When operating at a rotation frequency of the stepper motor shaft of $n_g = 68.6$ min^{-1}, the duration of the battery swapping cycle becomes $t_s = 223.5$ s.
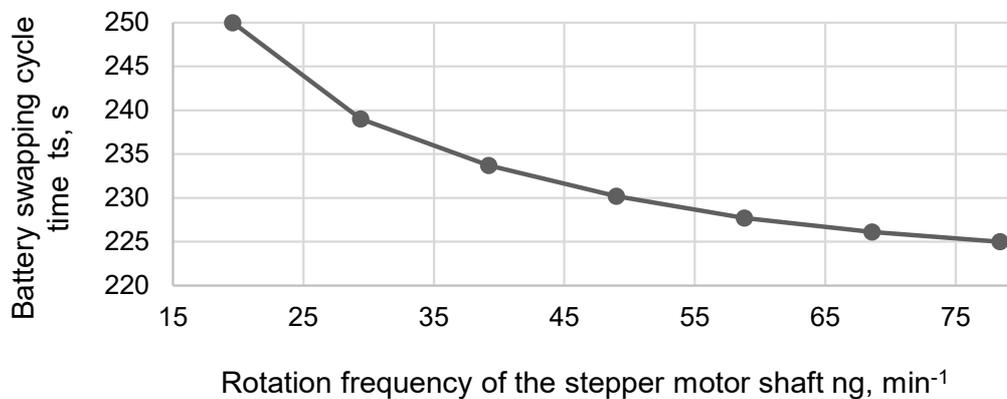

Figure 9. Dependence of the battery swapping cycle time t_s on the rotation frequency of the stepper motor shaft n_g.

The actual transverse movement time t_p of the battery cart, according to Eq. (6), is $t_p = 8.7$ s. During the verification test, it was found that the actual transverse movement time t_p of the battery cart differed from the theoretical value. Fig. 10 illustrates the difference between the theoretical and actual linear velocities of the battery cart depending on the rotation frequency of the stepper motor shaft n_g. Throughout the entire battery swapping cycle, the time for acceleration and deceleration is constant, with a duration of $\Delta = 1.5$ s, while only the average speed of the battery cart changes. That is, the

time spent on acceleration and deceleration is not accounted for at the calculated speed. The greater the rotation frequency of the stepper motor shaft n_g, the larger the difference between the calculated and actual times, which is associated with the increased proportion of time spent on acceleration and deceleration during the entire cycle.
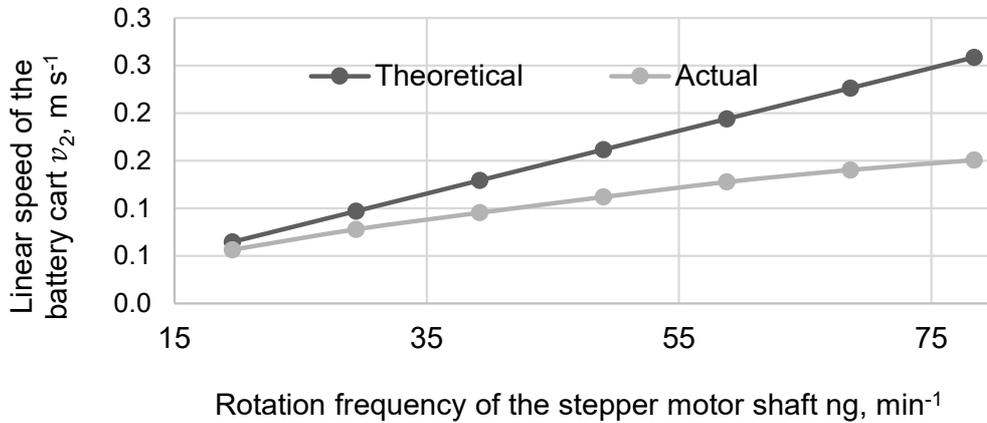

Figure 10. Comparison of the theoretical and actual linear speed v_2 of the battery cart as a function of the rotation frequency of the stepper motor shaft n_g.

The actual time for the lateral movement of the battery cart was 7.3 s longer than the theoretical time, resulting in a total of 16 s, including the time required for acceleration at the start of the movement and deceleration before stopping.
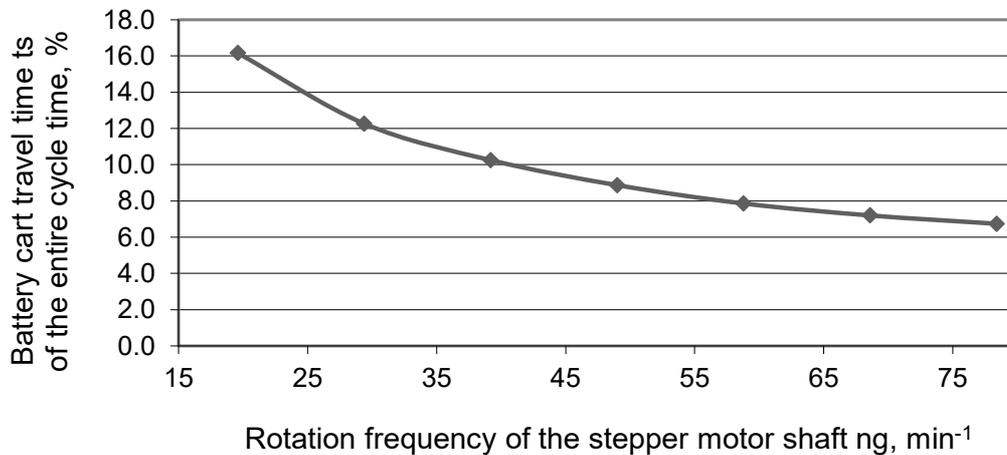

Figure 11. Percentage of total cycle time attributed to the movement of the battery cart, depending on the rotation frequency of the stepper motor shaft n_g.

The line in Fig. 11 represents the time required for the movement of the battery cart depending on the rotation frequency of the stepper motor shaft n_g. At shaft rotation frequencies $n_g = 50...75$ min^{-1}, the cycle time t_s changes by only 1.53%, which means that after $n_g > 50$ min^{-1}, further increases in rotation frequency have a negligible effect on the battery swapping cycle time.

The operations comprising the battery swapping cycle and their numerical values are presented in Table 1.

Table 1. Components of the battery swapping cycle and their values

Operation	Time, s
Longitudinal movement time of the battery container t_a	199.5 ± 1.59
Transverse movement time of the battery cart t_c	16 ± 0.04
Time for operating relays and locks t_l	8 ± 0.02
Total cycle time of battery swapping t_s	223.5 ± 1.65

The optimal rotation frequency of the electric motor determined in this study enabled the achievement of one of the primary objectives: constructing a battery swapping device capable of completing the battery replacement cycle within 240 seconds.

Further prospects and development:

1. Scalability for Diverse Agricultural Applications: While this prototype is designed for a specific agricultural robot, the modular and adaptable nature of the system allows for its potential application to other agricultural and industrial robots, broadening its utility.

2. Integration with Autonomous Fleet Management: The developed battery swapping unit could be integrated into larger systems for managing fleets of agricultural robots, optimizing battery usage, and enabling synchronized multi-robot operations.

3. Energy Optimization and Monitoring: Incorporating real-time energy monitoring and predictive analytics could enhance the system's efficiency and reliability, further reducing maintenance requirements.

4. Future Research Directions: The study lays the groundwork for further innovations in autonomous servicing technologies, including developing fully modular service stations capable of supporting additional robot maintenance tasks, such as diagnostics and minor repairs. Future research should include extensive field tests to evaluate the unit's performance under varying environmental conditions, such as dust, moisture, and temperature fluctuations, to ensure long-term reliability and robustness.

This innovative solution not only meets the immediate servicing needs of agricultural robots but also sets a benchmark for future advancements in autonomous agricultural systems. By enabling sustainable and efficient field operations, it contributes to the broader goal of enhancing productivity in precision agriculture while reducing labour dependency and environmental impact.

The autonomous agricultural robot, service station, and battery swapping unit developed at the Estonian University of Life Sciences can be integrated into various stages of the three-stage model described in the article Kiani et al. (2022) as follows: During the sowing stage, the robot precisely places seeds using navigation systems and sensors, while the service station ensures a continuous supply of resources such as fertilizers and seeds, and the battery changer enables autonomous operation by minimizing downtime. During the cultivation stage, the robot utilizes integrated sensors to monitor plant and soil conditions, perform precise fertilization, and regulate irrigation, while the service station replenishes water and fertilizer supplies, and the battery changer ensures uninterrupted operation. This integration optimizes each stage of the agricultural cycle, reducing time and energy costs while promoting sustainable farming practices.

CONCLUSIONS

The battery swapping unit presented in this article significantly improves the efficiency of battery replacement in agricultural robots by reducing transport distances and minimizing the number of moving parts. The design eliminates the need for vertical movement of heavy batteries, ensuring that all motions are confined to the horizontal plane, thereby enhancing operational safety and reliability.

A preliminary study on the research and development of the battery swapping unit revealed a lack of global technical solutions for the autonomous battery replacement of agricultural robots. Furthermore, existing battery swapping technologies for drones and vehicles are incompatible with the unique structural and functional requirements of the agricultural robot and mobile service station developed by the Estonian University of Life Sciences.

This article introduces a prototype of an original battery swapping unit developed during the research and development process. The device is specifically designed for the agricultural robot under development and its servicing requirements, such as minimizing maintenance time. Additionally, the proposed technical solution enables the selection of the optimal rotation frequency of the stepper motor, ensuring appropriate battery cart speed. The design carefully incorporates the structural and kinematic parameters required for seamless operation of the developed battery swapping unit.

The innovative battery swapping unit integrated into the developed service station achieves its primary purpose: automatically replacing a depleted battery with a charged one during operation. Moreover, it fulfils the requirement of completing the battery replacement within the timeframe allocated for other robot servicing operations, such as refilling the fertilizer hopper or pesticide tank, which is limited to 240 seconds. The developed unit successfully operates within this constraint, completing its cycle in just 223.5 seconds. This ensures seamless integration into the robot's service workflow.

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