DESIGN OF REMOTE-CONTROLLED GROUND BASED AIRCRAFT TUG

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Abstract

The article focuses on presenting the stages of designing a remotely controlled tow tractor with an electric motor - CRAWLER 01. The construction of the tow tractor is discussed in the context of the dynamic growth of the aviation sector, particularly in supporting ground handling of aircraft. Utilizing SolidWorks software, the process of creating tow tractor components is described in detail. Additionally, a preliminary strength analysis of the tow tractor was conducted, along with prospects for its further development, which is a key area of interest. The paper includes conclusions drawn from the conducted analysis and the achievement of goals. The compatibility of the developed preliminary design of the remotely controlled tow tractor with partial assumptions is emphasized. The work expands knowledge in the fields of machine design, electrical engineering, materials science, and the strength of materials and structures. Conclusions suggest that the developed tow tractor can effectively support ground handling of aircraft, contributing to time and cost savings both during potential construction and airport operations.

Keywords: tug, aircraft, reduced stress, project CAD, CRAWLER 01

1. Introduction

Traditional aircraft tugs, used in the "Pushback" procedure, are essential in ground operations at airports but present several challenges. Due to traction requirements, these tugs must be specially weighted with ballast, increasing their mass and fuel consumption. There are two types of tugs: conventional and "towbarless" (TBL), the latter being devoid of a towing bar. Conventional tugs utilize a hook or tow bar to connect to the aircraft and require special adapters for different types of aircraft, complicating and prolonging maneuver preparation times [1]. In response to these challenges, technological development has shifted towards remotely controlled tugs equipped with electric motors [2, 3, 4]. These modern devices not only eliminate the need for heavy ballast but also reduce greenhouse gas emissions, providing a more sustainable alternative to traditional combustion engine tugs. Thanks to remote control, these tugs minimize the need for physical involvement of ground personnel, enhancing safety and reducing operational costs [5, 6]. The "CRAWLER 01" model stands out among available market solutions by incorporating innovative Omni-Directional Wheels, which the authors consider a significant improvement. These unique wheels allow for much greater maneuverability and precision, facilitating operations in tight airport spaces. This innovation, combined with an eco-friendly electric drive, positions the "CRAWLER 01" as a model example of future technologies in the field of ground aircraft handling, promoting operational efficiency while minimizing negative environmental impact.

2. Project

In the context of the dynamically developing general aviation sector, with an increasing number of light aircraft weighing up to two tons and expanding aviation infrastructure, a range of technical and logistical challenges arise. Specifically, difficulties are associated with maneuvering aircraft on aprons without using engines, which presents a particular challenge on airfields with inferior surface quality. Traditional methods, relying on physical human strength or the use of conventional tugs, often prove insufficient due to limited staff availability or the specific characteristics of the terrain.

Therefore, the design of a remotely controlled ground-based aircraft tug (Fig. 1) appears to be a suitable response to these challenges.

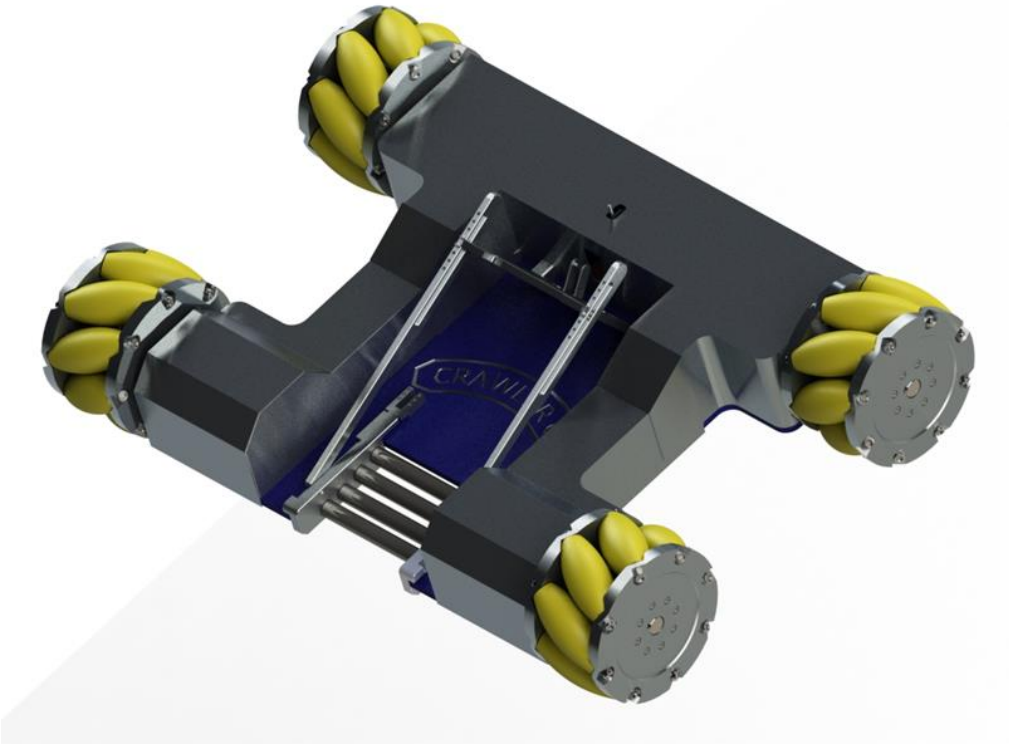

Figure 1 – Design of the CRAWLER 01 tug.

This design incorporates the use of modern technologies and innovative engineering solutions that can operate effectively even on less suitable surfaces, such as grassy areas. The compact dimensions (Fig. 2) and the weight of the tug, which is only 56 kg, facilitate its easy transportation both by land and air. These dimensions allow the device to be placed in an aircraft's cargo hold, enabling its use at foreign airports without the need for permanent on-site storage.

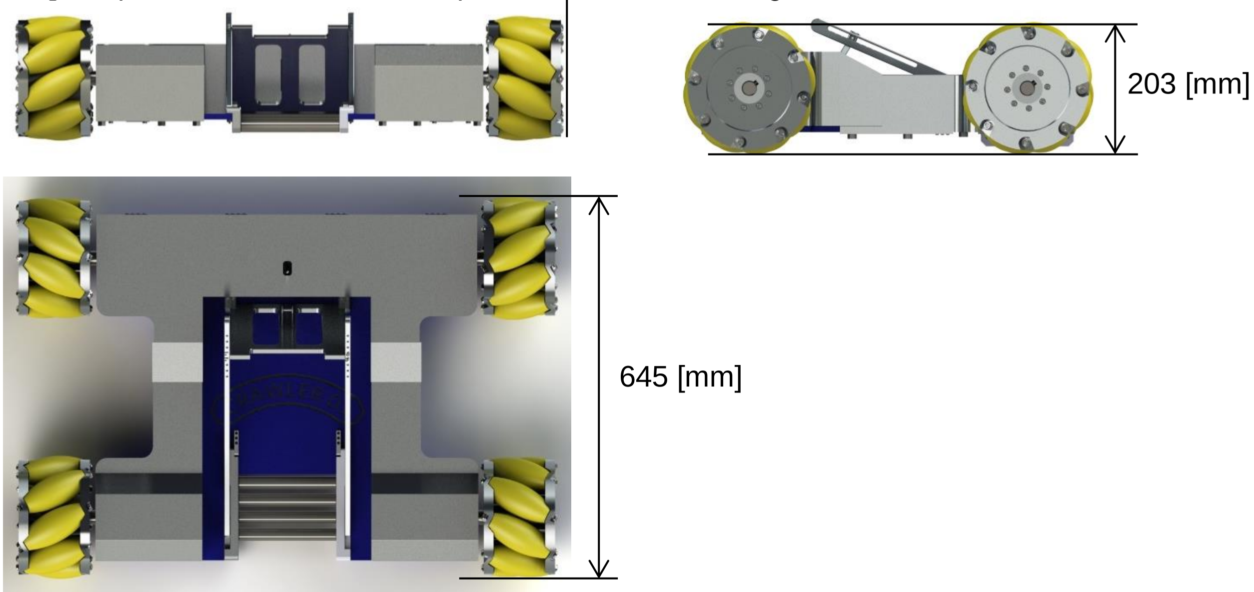

Figure 2 – Views of the "CRAWLER 01" tug with dimensions.

This mobility not only provides greater flexibility in aviation operations but also significantly facilitates the storage of the device. The size of the tug, compared to the DA-20 aircraft, is depicted (Fig. 3).

Figure 3 – The front landing gear of the Diamond DA-20 aircraft on the designed CRAWLER 01 tug.

Operating the tug offers significant flexibility through the ability to be controlled by a single individual using a straightforward radio controller with a range of up to 100 meters. Alternatively, the device can also be controlled via a smartphone, which connects to the tug through an integrated Bluetooth module. To facilitate operation, a dedicated mobile application will be developed, featuring an interface with buttons on the smartphone screen, allowing intuitive steering of the tug. Details are illustrated in Figure 4, demonstrating how mobile technology can support aviation operations at modern airports.

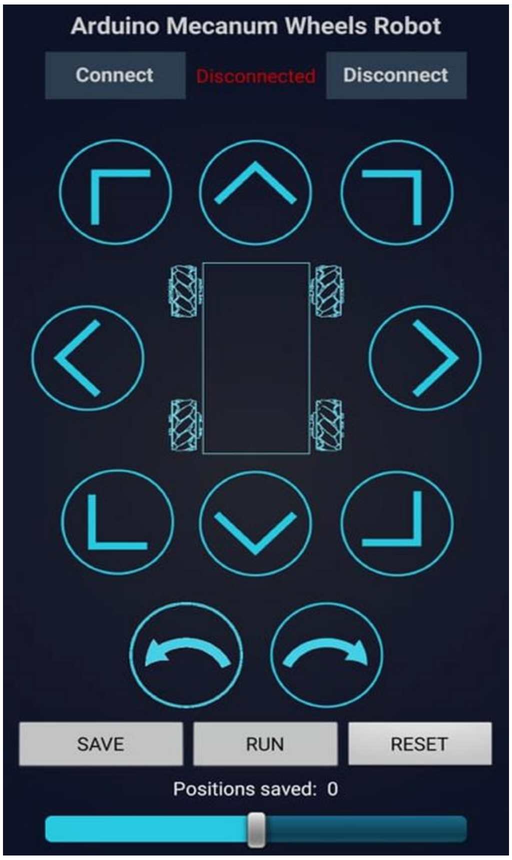

Figure 4 – Example of an application for a remotely controlled vehicle [7].

An innovative solution implemented in the tug design is the use of Omni-Directional Wheels (Fig. 5, 6). These wheels consist of two discs connected by pins, between which rollers are positioned at a 40-degree angle relative to the axis of travel (Fig. 6). This configuration allows the rotation of the wheel to generate a resultant force directed at an angle to the axis of rotation. Depending on the direction of rotation and the orientation of the rollers, which can be set to either the left or right side, this force can be directed opposite to the direction of travel.

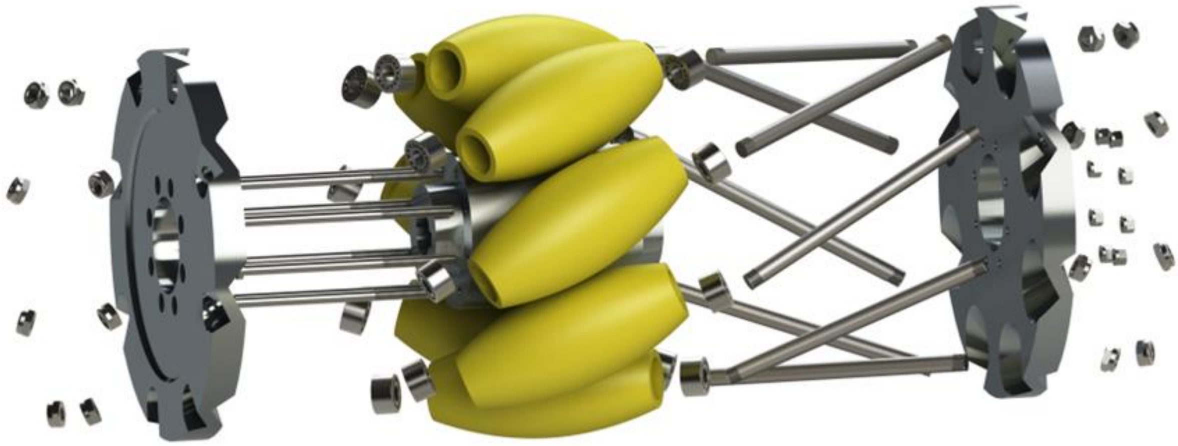

Figure 5 – Exploded view of the “Omni wheel” assembly.

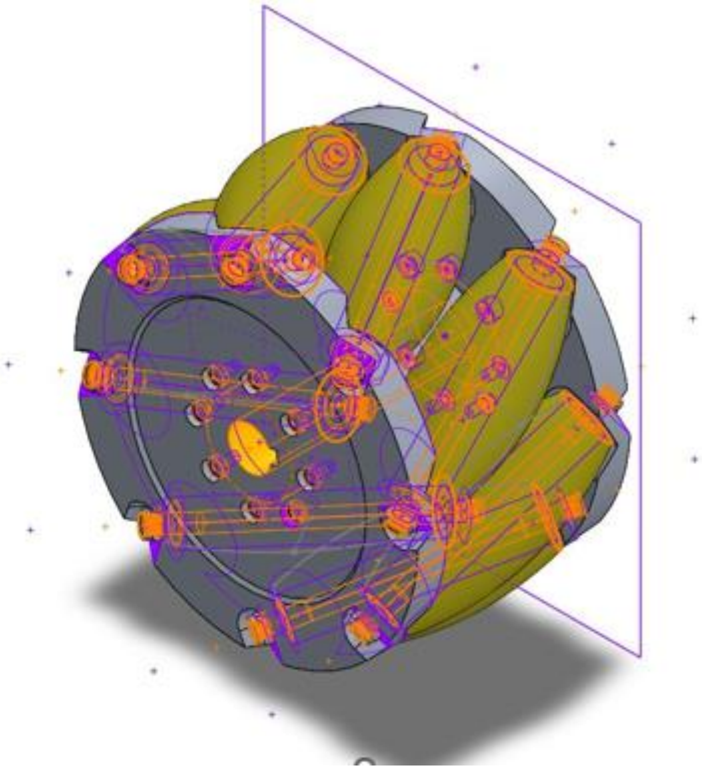

Figure 6 – Assembled view of Omni wheels.

Each wheel is powered by an independent motor, allowing for precise control of the resultant force for each wheel, enabling the vehicle to maneuver in any direction without the need to rotate around its own axis. This feature enhances the maneuverability of the tug, making it an excellent tool for use in confined spaces such as airports or hangars.

The tug is powered by four “Scorpion HK-7050-340KV” brushless motors, which are characterized by a maximum nominal power of 10 kW and a maximum current of up to 200 A (Fig. 7). These motors, known as BLDC (Brushless DC), were selected for their higher efficiency, longevity, and better performance compared to brushed motors. A significant feature of BLDC motors is their controllability via feedback mechanisms, which allows for precise power regulation and reduction in energy consumption and heat emission. These properties, especially with battery power, significantly extend battery life.

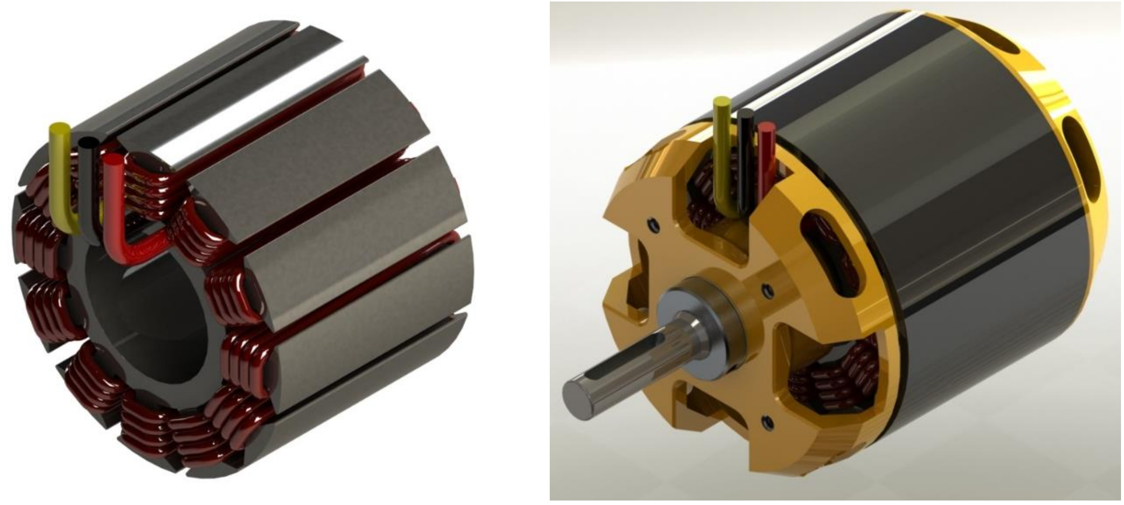

Figure 7 – Rendered images of the rotor and assembly of the Scorpion HK-7050-340KV brushless motor.

Considering the motor classification of 340 Kv, it is possible to calculate the speed at which the tug will move. Initially, the revolutions per minute (RPM) for the unloaded motor shaft are calculated, then reduced by the factor of a 16:1 planetary gear ratio and the influence of load and system efficiency. Assuming a motor efficiency of about 90% and further reducing it by an additional 10% due to the load of the vehicle and the aircraft, precise drive parameters can be determined, consequently allowing movement at a speed of approximately 2 m/s. This speed range is suitable for freely maneuvering various types of aircraft. To achieve the appropriate speed and efficiency of the vehicle, the project's authors implemented a mechanical gearbox. Although the design of the gearbox depends on the type of device, there are common features characteristic of all mechanical power transmission systems. Due to numerous advantages, the authors' choice fell on a planetary gearbox. The construction of the planetary gearbox (Fig. 8) consists of two concentric gears: a sun gear (central) with external teeth and a ring gear (external) with internal teeth. Between these gears are placed satellites, or small gears, which rotate around their own axes while also orbiting the axis of the entire mechanism. This particular configuration allows for three different gear ratios, enabling effective power transmission and regulation, making this gearbox ideal for use in tugs with high power requirements.

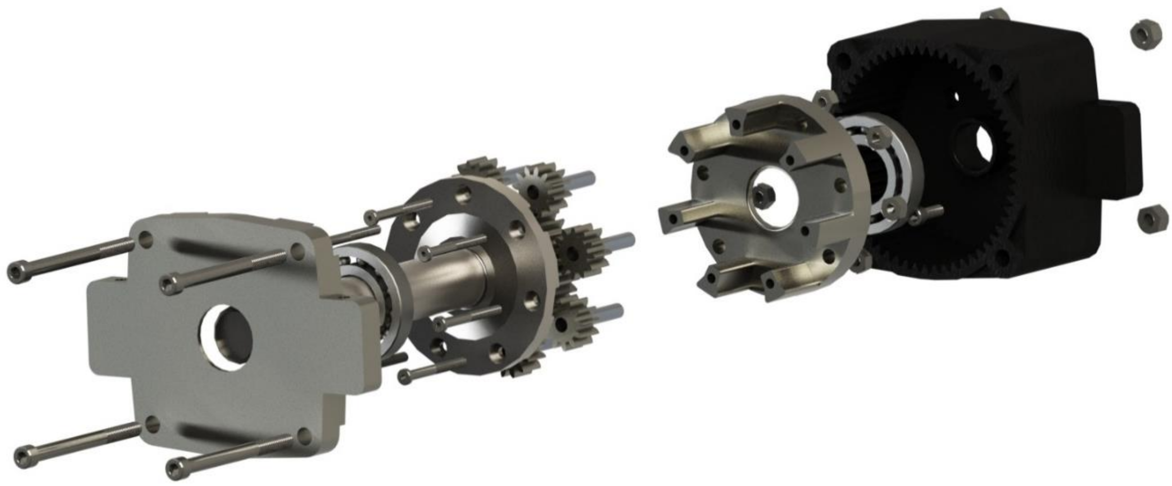

Figure 8 – Exploded view of the designed planetary gearbox.

Impact of the cradle design on the efficiency of aircraft towing
The cradle plays a crucial role in the aircraft towing process, influencing one of the most important operational parameters – the time it takes to load the aircraft onto the tug. Reducing this time directly enhances the tug's usability, which is significant for its owner.
Design of the fork and connector
The notch on the outside of the fork is designed to create space for connecting the fork to the connector while ensuring an adequate distance between the housing and the cradle. The design of the connector is relatively simple: it is a profile with a hole at one end, to which the fork is attached using a pin. At the other end, there is a slot where the end of the flap is placed, allowing it to move as if on a rail.
Flap locking mechanism
At the top of the connector, there are holes that prevent uncontrolled movement of the flap. Pins can be inserted into these holes, which lock the movement of the flap's tip along the edge of the connector while allowing it to rotate around its own axis. The flap is inclined at a slight angle to the base, enabling interaction with the wheel entering the tug's platform. The flap moves, closing behind the forks and preventing the wheel from rolling off the platform.
Latch functionality
The latch at the rear of the flap serves to lock it in the closed position. Initially, the latch rod is placed in the lock hole, and then by pressing, it releases the lock. Once the latch passes the lock, the lock closes. The latch rod is extended between two walls, providing stability to the mechanism. The entire assembly of the cradle is shown in Figure 9.

Figure 9 – Assembly of the cradle.

The locking mechanism (Fig. 10) in the cradle is a key component that maintains it in the closed position. The entire mechanism is housed within the lock casing, and its triangular cutout allows for the insertion of the latch, which is locked in this position. Closing the casing prevents contaminants from entering the mechanism, ensuring its long-term and fault-free operation. The hole at the bottom of the casing is for the insertion of a servo mechanism shaft, which allows for precise control of various physical processes. The function of the servo mechanism is to retract the lock, thereby releasing the latch, the flap, and the aircraft wheel. The pusher, a vertical rod located below the lock, is used to unlock it via the action of the servo mechanism. The top part of the lock has been shaped to fit perfectly into the lock casing to prevent any notch effect that could weaken the mechanism. When the flap latch moves towards the lock, it presses on the lock, which opens by rotating on a pin. Afterward, a spring closes the lock, ensuring the stability of the mechanism. During the unlocking by the tug operator, the servo mechanism rotates a blade through the hole at the base of the casing, pressing on the pusher. This action opens the lock, allowing the release of the latch and movement of the flap, which in turn enables the free movement of the aircraft wheel.

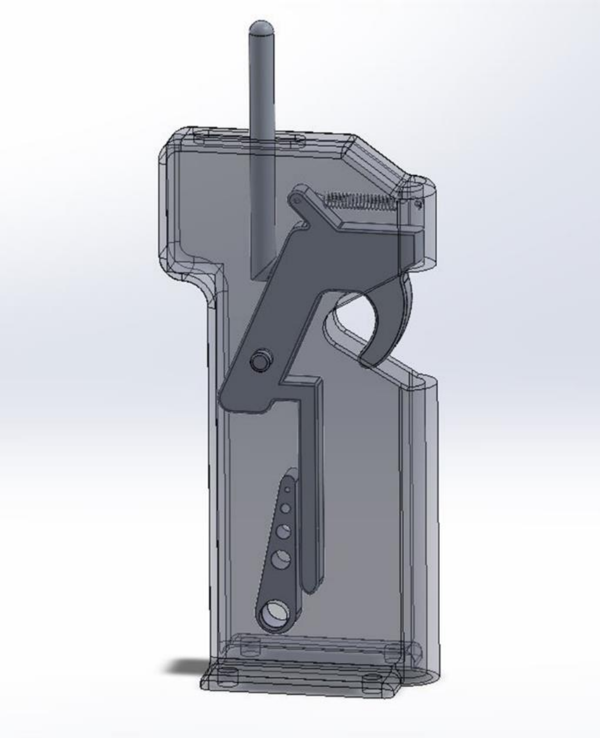

Figure 10 – Locking mechanism.

In the design process of the tug, particular attention was paid to the type and placement of wiring, as well as the positioning of batteries, servo mechanisms, and PCBs (Printed Circuit Boards) (Fig. 11). The wires were meticulously attached to other assembly components using adhesive holders. This arrangement allows for easy localization and identification of the specific wire in the event of an electrical system failure.

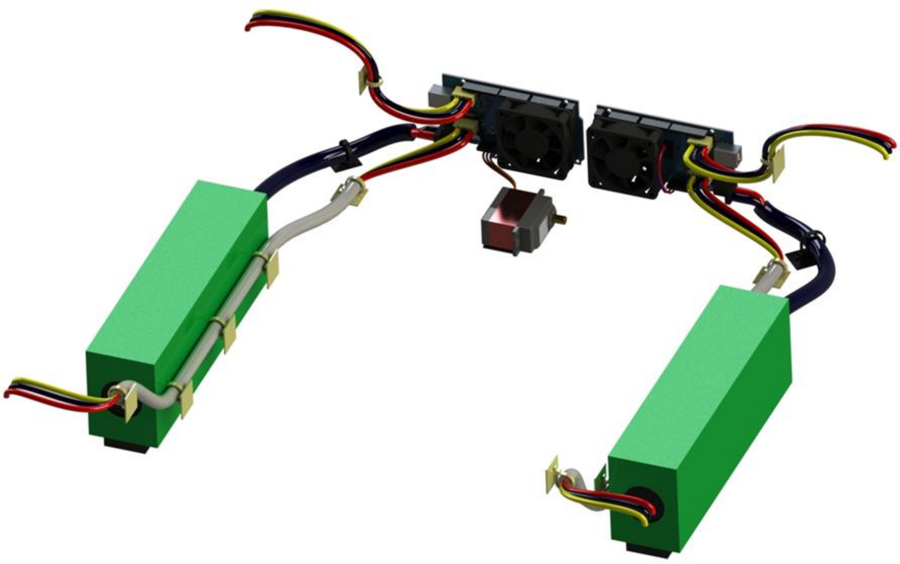

Figure 11 – Electrical installation and wire layout.

In the context of advancing technology and increasing demands for the efficiency of aviation operations, a discussion of the various towing phases becomes essential. A precise presentation of each towing phase (Fig. 12) allows for an understanding of both the mechanisms of the tug's operation and the operational requirements that must be met to ensure the efficiency and safety of the entire process. This presentation of the stages is crucial for both airport operators and the technical teams responsible for the maintenance and operation of tugs.

Towing Phases:

First phase	This phase begins with positioning the tug under the aircraft's nose wheel, which is typically the front wheel. The cradle of the tug is aligned with the longitudinal axis of the aircraft, which is crucial for ensuring stability during towing.
Second phase	Securing the main landing gear of the aircraft is crucial, for example, using blocks or wedges, to prevent the aircraft from shifting while maneuvering the tug. Subsequently, the tug approaches the landing gear, and the rollers mounted on it, which are supported by two high-load roller bearings, facilitate the entry of the landing gear wheels onto the tug's platform.
Third phase	This phase involves placing the steering wheel on the tug's platform. The tug approaches the front wheel, and the rollers on the front forks help overcome friction forces, facilitating the loading of even larger aircraft.
Fourth phase	The final securing of the steering wheel in the tug's cradle. After placing the wheel on the platform, the tug moves further along the aircraft's longitudinal axis, pulling the forks which in turn move the rear flap. The latch mechanism on the rear part of the flap activates the lock. Once the latch surpasses the lock, an integrated spring closes the lock, preventing the wheel from dislodging.

The third and fourth phases should be executed in one fluid motion to prevent the wheel from rolling back and to effectively overcome the forces acting on the axes of the cradle and the locking mechanisms. Each of these phases is crucial for the safety and efficiency of the towing process, enabling smooth and controlled movement of the aircraft.

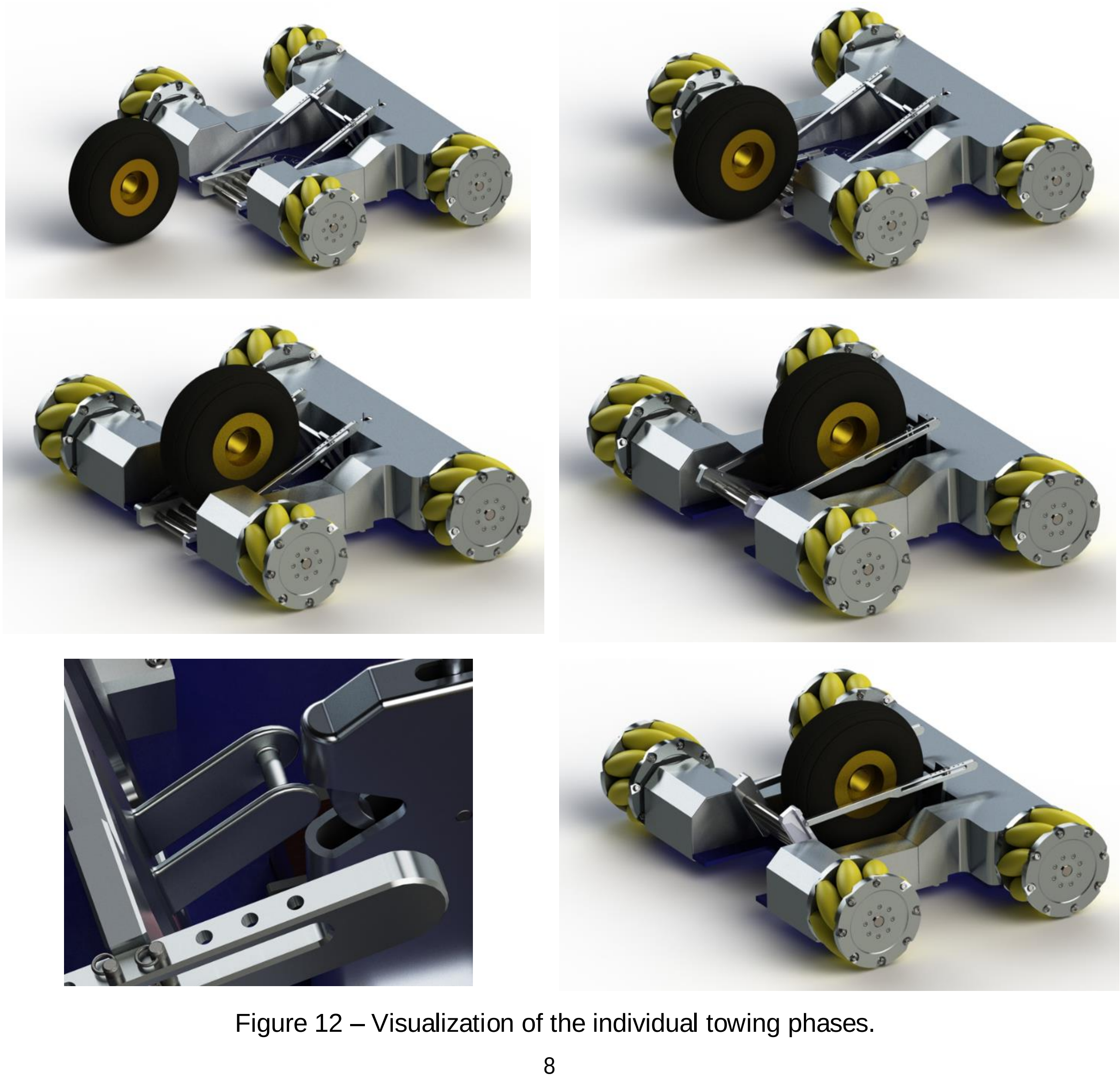

Figure 12 – Visualization of the individual towing phases.

3. Results and discussion

Within the fundamental stages of designing a ground-based aircraft tug, a preliminary structural analysis of a mechanically loaded component during planned operation was conducted using the Simulation module of SolidWorks software. For the static analysis, a simulation was performed to determine the stresses, deformations, and displacements in the model under the continuous pressure of an aircraft on the tug's platform. The results of the simulation were appropriately illustrated in the drawings. The material used in the simulation was 2024-T3 aluminum alloy, characterized by its main alloying element, copper, and a tensile strength of 400-430 MPa. The T3 tempering process provides material strengthening. The analysis was conducted on a mesh consisting of 75,392 elements and 129,836 nodes. The model's fixtures were applied as fixed in six screw holes at the corners of the base. The simulation accounted for a pressure equal to 20-30% of the weight of an aircraft weighing 1000 kg on the front landing gear, which translates to an external force of 2500 N, acting on a rectangle simulating the contact surface area of the aircraft wheel with the platform. The obtained stress results (Fig. 14) showed that the highest stress value was 149.5 MPa, occurring only in limited areas with sharp endings, which is less than half of the yield strength of the used material, which is 345 MPa. This indicates that the yield limit was not exceeded, confirming the adequate strength of the tug's structure under load (Fig. 13).

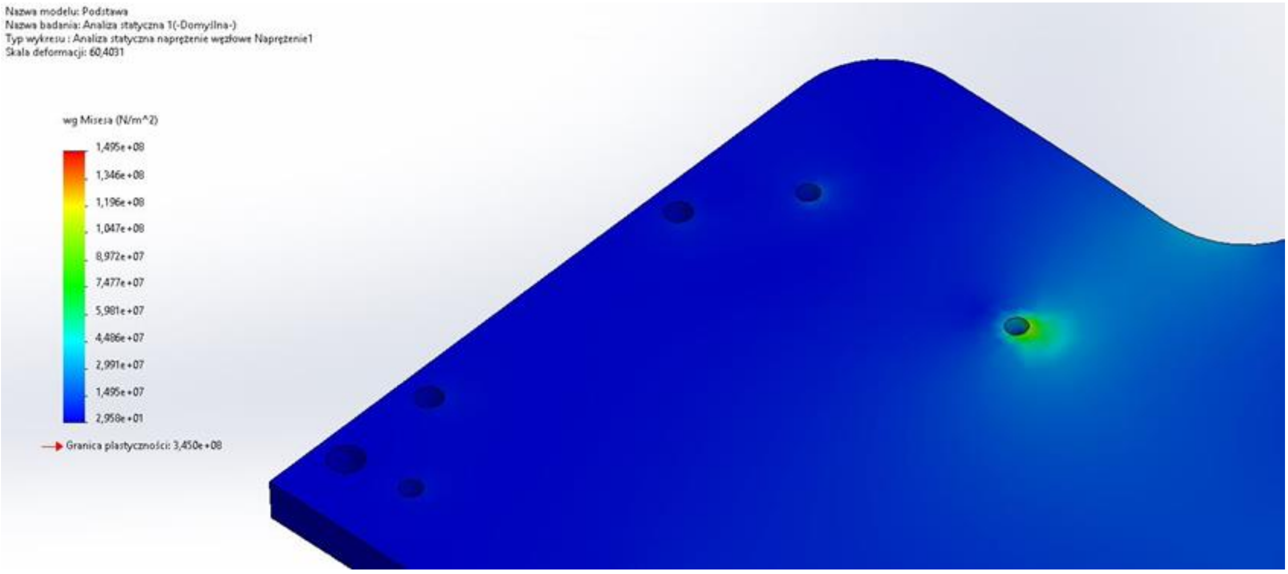

Figure 13 – Location of the highest stress concentration on the CRAWLER 01 tug platform.

The simulation analysis also provided information on the displacements and deformations of the tug platform. The maximum recorded displacement was 1.093 mm (Fig. 16), and the largest deformation reached a value of $1.302 \cdot 10^{-3}$ [-] (Fig. 15). Both the displacements and deformations remain within safe limits, indicating the appropriate strength and stability of the structure under operational conditions. These results confirm that the tug platform meets the required strength criteria and is capable of effectively transferring loads resulting from usage.

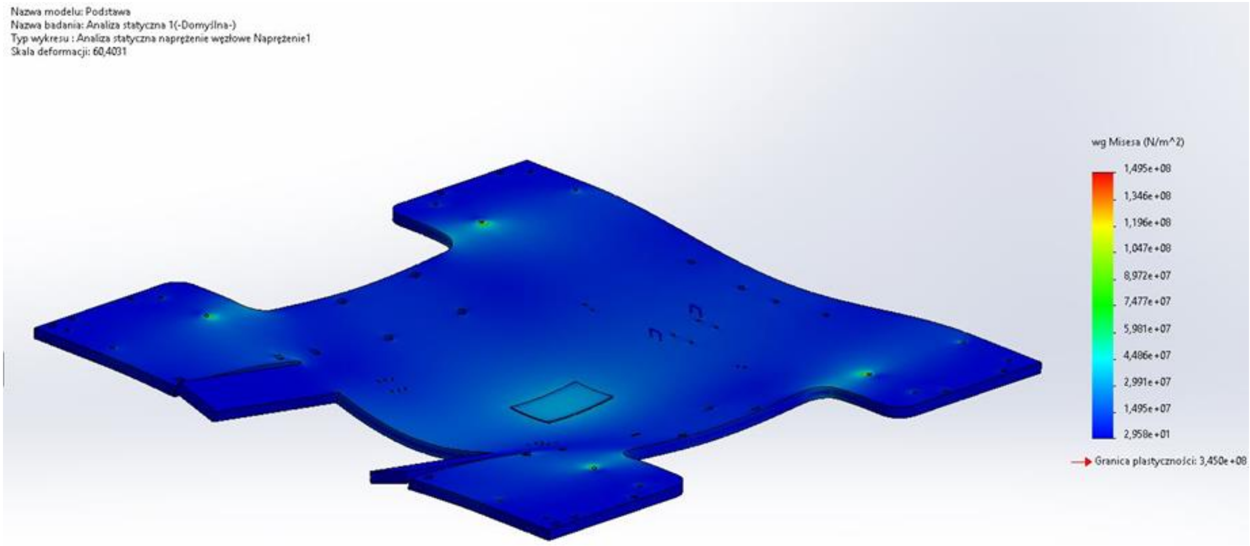

Figure 14 – Distribution of reduced stresses according to the Huber-Mises hypothesis on the CRAWLER 01 tug platform.

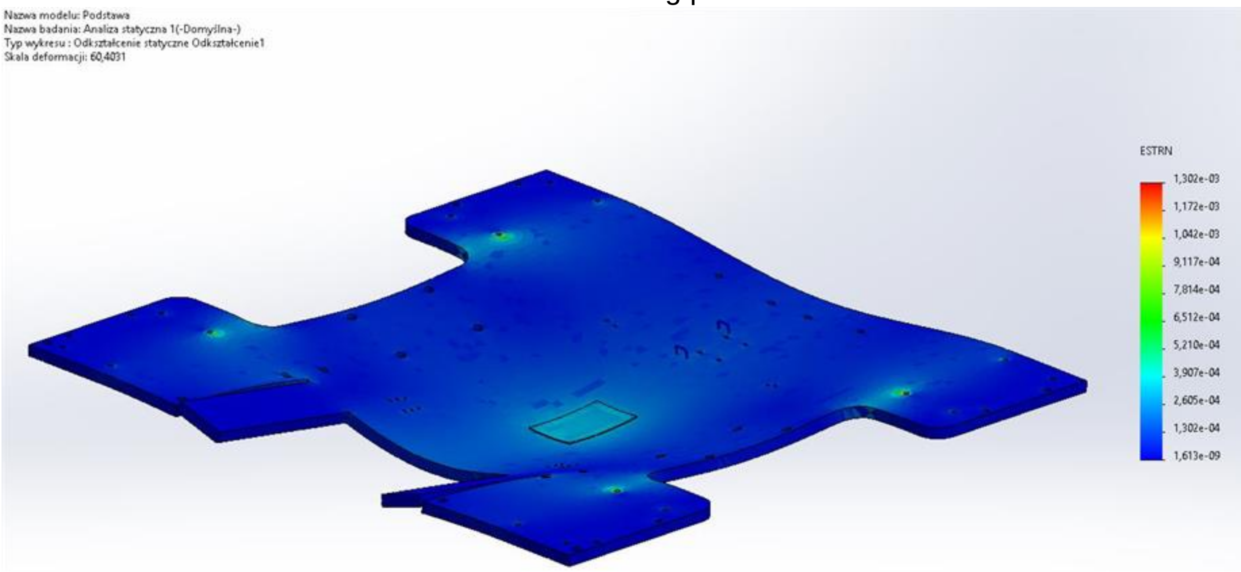

Figure 15 – Distribution of deformations on the CRAWLER 01 tug platform.

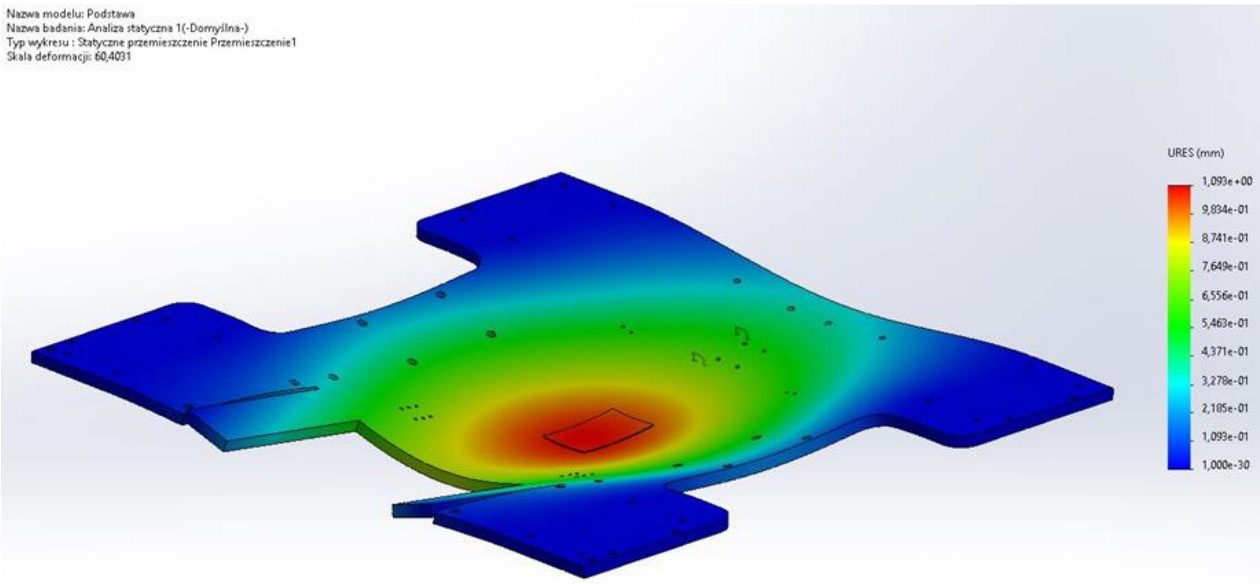

Figure 16 – Distribution of displacements on the CRAWLER 01 tug platform.

4. Conclusion

The conclusions drawn from the preliminary design of the remotely controlled tug CRAWLER 01 and the conducted numerical studies are promising and indicate many potential benefits for the aviation sector. Key aspects emerging from the project analysis include the mobility of the tug, the application of omni-directional wheels, and prospects for development towards an autonomous system. The use of a mobile tug with an electric motor, as presented in the CRAWLER 01 project, provides a significant advantage in the ability to transport it in the aircraft's cargo hold. This unique feature markedly differs from other tugs, which do not offer such capability. Transporting the tug in the cargo hold creates new operational opportunities at airports, especially in locations with few aviation operations. The application of omni-directional wheels allows the tug to operate in all directions without the need to change the position of the aircraft. Unlike traditional tugs, which have limited steering angles of the main landing gear, CRAWLER 01 can move freely, enhancing the efficiency of ground handling. Developing the project towards an autonomous system is a key step for the future. The tug as a mobile robot can be autonomized, which would contribute to more efficient airport operations. Automating processes related to towing aircraft could lead to savings in time and resources. Additionally, the basic strength calculations performed using simulation computations confirmed that the structural conditions were not exceeded during the operation of the presented tug.

5. Copyright Statement

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