TECHNOLOGY, CREATIVITY, IMPLEMENTATION

CONCEPTUAL PRINCIPLES FOR IMPROVING THE MANEUVERABILITY OF MODULAR ROAD TRAINS FOR AIRFIELD TECHNICAL SUPPORT OF FLIGHTS

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Summary

The purpose of the research is to find directions for the development and substantiation of engineering solutions and technical methods aimed at increasing the maneuverability of modular road trains in the context of specific conditions for the airfield environment. The evolution of methods of improving maneuverability of modular road trains for airfield technical support of flights is possible on the basis of measures to optimize design of the coupling and control unit, the use of energy modules, the use of mechatronic active control systems, standardization, unification, modeling and analysis of kinematic parameters, assessment of stability and safety during maneuvering. An integrated approach that combines engineering, information and organizational solutions makes it possible to create efficient, safe and adaptive new generation modular vehicles that reduce number of aircraft maintenance equipment at an airfield without losing functionality, reduce maneuvering time by 27%, aircraft maintenance time by 18–25% and reduce the risk of collisions.

Key words: airfield ground support, operation of automobile chassis, modular systems, motion stability, controllability and maneuverability.

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1. Introduction

Airfield technical support plays a critical role in the operation of modern aviation, especially in military or emergency conditions. Modular road trains are key vehicles that ensure prompt delivery of technical equipment, fuel, and aircraft maintenance facilities. The high level of maneuverability of such road trains is a prerequisite for the effective functioning of the system of preparing aircraft for departure in the confined spaces of airfields *(Kaviuk & Kashkanov, 2024)*.

The maneuverability of a road train is understood as its ability to perform turns, turns and other maneuvers in confined space without losing stability or safety *(Pacejka, 2012)*. It is determined by a number of parameters, in particular: turning radius (internal and external), folding angle between a tractor and a trailer, overall lane, center of mass coordinates, and type and design of trailer link steering. Maneuverability is influenced by length of a road train, the presence of steerable axles, some type of clutch, and wheel steering algorithms.

An analysis of the research shows that improving the maneuverability of modular road trains for airfield technical support of flights can include several key methods:

− optimization of the connecting and controlling unit design – improvement of hinge connection to increase reliability and reduce load *(Baranov & Pavlyuk, 2020)*;

− use of energy modules – the transition to wheeled energy modules allows expanding range of equipment with a minimum number of basic modules *(Podrigalo et al, 2023)*;

− application of active control systems – electronic stabilization and adaptive control systems to improve maneuvering accuracy *(Lowe & Guvenc, 2023; Kolisnyk et al, 2024)*;

− standardization and unification – development of common standards for aircraft ground handling, which contributes to efficient use of equipment *(Medynskyi, 2021)*;

− modeling and analysis – use of software for numerical analysis of optimal kinematic parameters during turns, turns, and the "permutation" maneuver *(Liu et al, 2021)*; analysis of the impact of layout schemes on the overall traffic lane *(Marchuk et al, 2025)*; assessment of stability and safety when maneuvering in confined spaces *(Jilek, 2025; Kolisnyk et al, 2023)*.

Despite a wide range of research, the issue of low maneuverability of modular road trains for airfield technical support has not yet been resolved, that often leads to delays, reduced efficiency of aircraft maintenance, as well as potential accidents in conditions of limited visibility or poor traffic management at an airfield.

The purpose of the research is to find directions for development and justification of engineering solutions and technical methods aimed at increasing maneuverability of modular road trains in the context of airfield environment specific conditions:

− presence of restricted maneuvering zones (e.g., near an aircraft, between hangars, inside hangars, in shelters, on aprons, in warehouses);

− requirements for positioning accuracy during aircraft maintenance;

− the need to reverse without folding links.

2. Organizational and technological features of aircraft maintenance by means of aerodrome technical support of flights

In modern conditions of intensive operation of aircraft, one of the critical elements of ensuring safe and continuous flight cycle is the effective functioning of the airfield technical support system. The technological process of aircraft maintenance includes performance of regulated operations in accordance with specialized technological cards developed for each type of aircraft and approved by the relevant aviation services.

Such cards include:

− a list of flight preparation activities;

− the sequence of refueling, recharging, and technical control operations;

− requirements for power supply, pneumatic and hydraulic maintenance.

The technological chain of these operations involves the Aerodrome Technical Support Equipment for Flight Operations (ATSEFO), which must be submitted to the designated aircraft:

- at a specific time (maintenance window);
- in the required quantity (depending on the type of the aircraft);
- ensuring a strictly defined sequence of movement in accordance with the aerodrome logistics route schemes.

The ATSEFO shall approach the aircraft in accordance with special approach and departure schemes (Fig. 1), which take into account:

- limited maneuvering space;
- configuration and dimensions of a particular type of aircraft;
- open service areas;
- technical safety zones.

In most cases, the designated ATSEFO service points are located on tail section or under wing sectors of aircraft. This implies the need to maneuver in the opposite direction, which significantly complicates the operation in conditions of:

- limited visibility;
- dense arrangement of infrastructure facilities;
- time constraints.

Movement of ATSEFO in reverse gear in close proximity to the aviation facility:

- creates a threat of mechanical damage to the aircraft;
- increases some load on an operator of the equipment;
- requires a high level of coordination and accuracy of stopping.

These conditions impose strict requirements on the tactical and technical characteristics of the vehicle, in particular to:

- inspection systems (cameras, depth sensors);
- controllability when changing the trajectory in reverse;
- availability of automated or intelligent driving support functions.

The modular design of the ATSEFO allows to meet the above requirements, as they are able to:

- provide versatility – easy adaptation to specific types of serviced aircraft;
- increase maneuverability – use of rotary sections and autonomous control;
- optimize operation by reducing weight, transformability, and compact storage.

Thus, modular automatic transfer switches should have:

- stable control when driving in reverse;
- ability to turn on a limited radius;
- precise positioning near the service area;
- ability to operate in non-standard infrastructure (shelters, hangars, parks, etc.).

3. Aspects of improving the maneuverability of airfield technical support

The search for ways to improve the tactical, technical, and operational characteristics of military equipment (ME) creates a need to conduct research on the design of multi-module ATSEFO on single-axle trailers and the necessity to ensure stable maneuvering control capabilities when reversing toward aircraft *(Kirichenko et al, 2017)*. A feature of modular road trains is the ability to transform configuration depending on the tasks, which creates additional challenges to ensure stable maneuverability.

In the theory of wheeled transport vehicles, which includes ATSEFO, the principle of steering, named after Ackerman, is known worldwide and was patented in the 19th century. In its modern form, the Ackerman principle is described by a mathematical formula that reflects the ration between the turning of the left and right wheels of a car *(Sakhno et al, 2021)*.

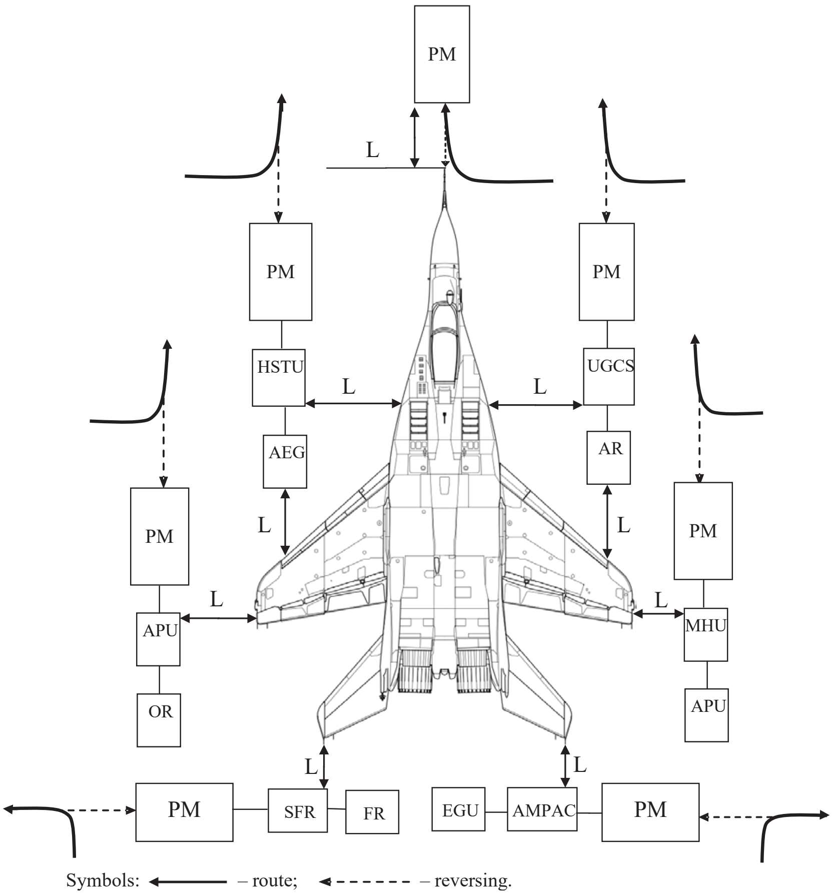

Fig. 1. Example of a special ATSEFO approach procedure for an aircraft

PM – power module, APU – airfield power unit, UGCS – unified gas charging station, HSTU – hydraulic system testing unit, FR – fuel refueler, AEG – airfield engine generator, SFR – specialty fluid refueler, AMPAC – airfield multi-purpose air conditioner, MHU – mobile hydraulic unit, OR – oil refueler, EGU – electric hydraulic unit, AR – air refueler

$$\mathrm{ctg}\gamma_L - \mathrm{ctg}\gamma_R = \frac{B}{L}, \tag{1}$$

Where γ_L – is the relative angle of the left wheel rotation; γ_R – is the relative angle of rotation of the right wheel; B – is the track (distance between pivot joints of left and right wheels); L – is the wheelbase (distance between swivel and non-swivel wheels).

The increased attention to the Ackermann steering principle in recent years has been caused by emergence of a large number of works on the theory of motor vehicle control *(Kashkanov & Palchevskyi, 2024)*: problems of navigation, trajectory control, autonomous control and maneuvering, etc.

We will consider a road train as an object of theoretical mechanics – mechanical system of connected solids *(Kuzo et al, 2017)*. Usually, the main task of theoretical mechanics is to obtain the law of motion, i.e., explicit dependence of all coordinates of a moving object on time without exception. Knowledge of the law of motion provides information about all properties of motion, i.e., complete information about motion. However, the law of motion is not the only way to represent information about motion. For example, if differential equations of motion and initial conditions are known, the law of motion can be obtained by integration (solving the Cauchy problem). This representation implicitly contains information about motion.

A generalized diagram of a multinodular airfield military vehicle with uniaxial trailer modules is shown in the Figure 2. It includes a power module (tractor), to which single-axle technological trailer modules with specialized equipment are hinged in front and/or behind. The number of technological modules can be varied. The location of the technological module in front of the tractor requires a number of technologies for performing work using:

- airfield thermal gas jetting machines;
- auger snowplows;
- mine clearance machines by trawling.

The technological module 1 in the form of a single-axle trailer with fixed wheels (for example, a rotary snowplow in the operating position) is pivotally attached to the energy module 2 (in the form of a serial truck), to which the technological module 3 is pivotally attached behind. There may be more modules – both in front and behind. The serial numbers 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 indicate the points of the road train to describe the configuration of the non-holonomic constraint system that determines the regularities of the course movement. SM4, SM6, SM11, SM13 are systems for monitoring the direction of movement of the points in which they are located.

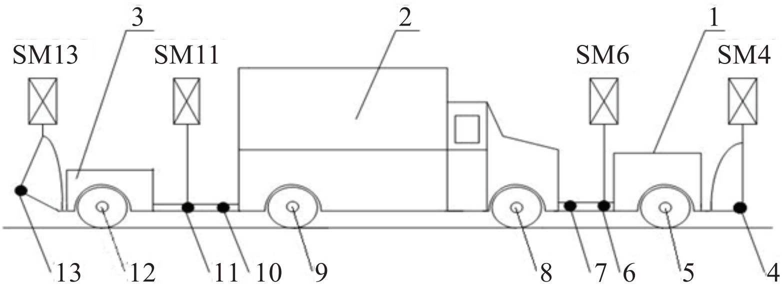

Fig. 2. Generalized model of a modular road train scheme

With regard to the automated traffic control systems under consideration (Fig. 3), the non-holonomic system (NHS) of each automated traffic control system is a sequential chain of hinged links with a certain number of non-holonomic constraints (NHC), which is always more than one. This set is the non-holonomic system.

Each wheeled motor vehicle has its own NHS configuration – this is a scheme for the placement of all NHS, all links of motor vehicle and articulated joints of links.

The description of the configuration should begin with numbering of the road train links in order (1, 2, 3, ...) and then continue with numbering on midline of the points at which all the non-holonomic constraints are located, the points of hinge connection of the links (7, 10,

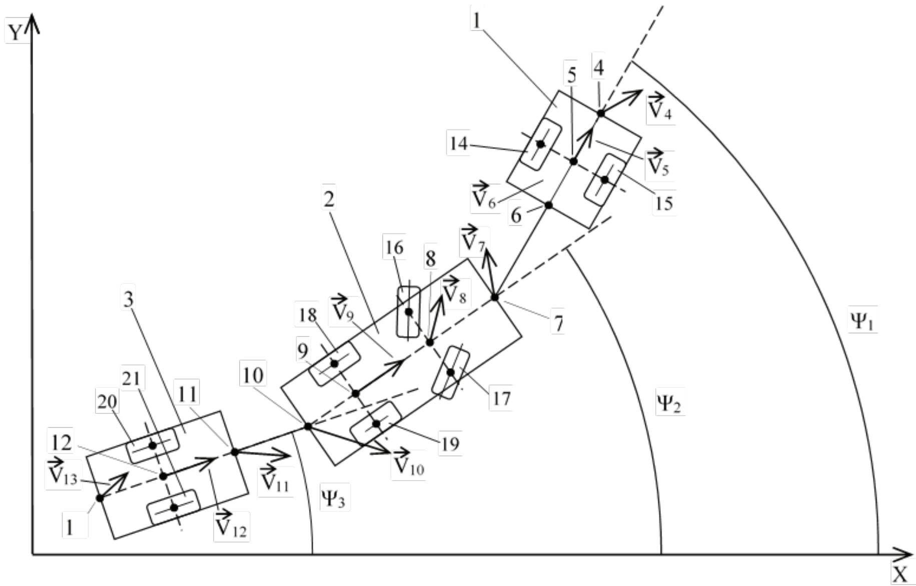

Fig. 3. Non-holonomic system of a generalized model of a two-link modular machine with one trailer attached to a tractor in front or behind

...) and the points whose movement is set or determined (4, 5, 6, 7, 8, 9, 10, 11, 12, 13, ...). At points 5, 8, 9, 12 are the axes of the motor vehicle with wheels, which are indicated by adding the letter L if the wheel is located on the left, and the letter R if on the right: 5L, 5R, 8L, 8R, 9L, 9R, 12L, 12R. At these points, a non-holonomic constraints of the motor vehicle with the road is imposed, which restricts the movement of this point "*i*" only along velocity vector. Within the area of non-holonomic constraints existence, they completely determine trajectories of curvilinear motion of all points of the road train, regardless of dynamic load. Of course, in analytical mechanics *(Kuzo et al, 2017)* all non-holonomic constraints are described by a differential equation that cannot be solved in finite functions (and can only be solved by numerical methods, which does not allow for analysis).

It is proposed to describe each non-holonomic constraint in a natural coordinate system (the time parameter "*t*" is replaced by the parameter "*s*" – movement along the path) in a parametric form and to consider in the model directly the velocity vector of the point "*i*" of the motor vehicle where the wheel is installed (Fig. 4). Accordingly, the equations for the non-steering non-holonomic constraint are written as follows:

$$\frac{dy_i}{ds_i} - \sin\psi_j = 0\,;\ \frac{dx_i}{ds_i} - \cos\psi_j = 0. \tag{2}$$

For a rotary non-holonomic constraint, the wheel has a running-in arm, so point "*i*" is located in the pivot on the link "*j*"

$$\frac{dy_i}{ds_i} - \sin(\psi_j + \gamma_i) = 0\,;\ \frac{dx_i}{ds_i} - \cos(\psi_j + \gamma_i) = 0. \tag{3}$$

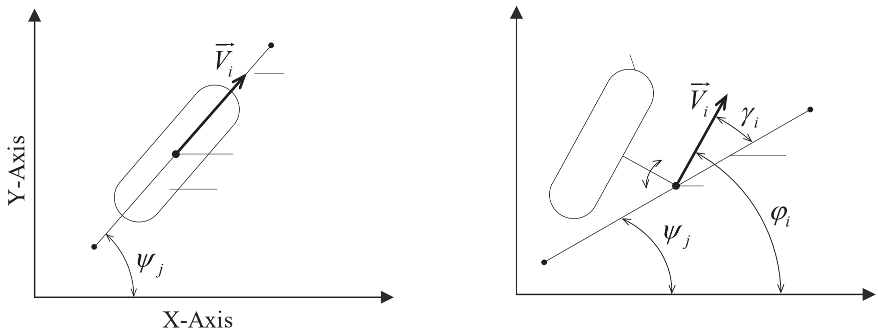

Fig. 4. Non-steering non-holonomic constraint (left) and steerable non-holonomic constraint (right)

Each point of the motor vehicle has its own trajectory (its coordinate "s_i"), so for each pair of points ("*i*", "*k*") it is necessary to additionally write a differential equation according to the Grasgoff theorem *(Hrechko & Perehon, 2023)*

$$\frac{ds_i}{ds_k} - \frac{\cos\gamma_k}{\cos\gamma_i} = 0. \quad (4)$$

This allows us to reduce the different coordinate systems of all points of the motor vehicle to a single one and obtain necessary solutions for analyzing curvilinear motion during maneuvering for any point of the motor vehicle. This method of equivalent transition in the equations from the time parameter to the path parameter allows creating an adequate mathematical description without using any additional simplifications, takes into account the speed and other speed parameters, takes into account all dynamic parameters because they are taken into account in the equations for describing non-holonomic constraints, both real and virtual. The model remains invariant to kinematic and dynamic parameters, just as when considering the Ackermann steering principle for a four-wheeled vehicle. The key here is to describe non-holonomic constraints model as real velocity vector of the point of the car where it is located.

It is possible to measure the angle of the real velocity vector of any point of a motor vehicle using angle sensor that is installed in self-pivoting wheel and placed at this point. If such a sensor cannot be installed at the required point, then the velocity vectors angles of other two points are measured and then the velocity vector angle of the required point of any motor vehicle link is determined by the recalculation method.

In order to increase maneuverability of modular road trains in the aerodrome ground support system, the following conceptual principles are proposed.

1. Integration of active control systems:

– use of electronically controlled steering drives on each module;

– implementation of algorithms for coordinating axle rotation depending on speed and trajectory;

– adaptive control based on sensor information (LiDAR – Light Detection and Ranging, GPS – Global Positioning System, IMU – Inertial Measurement Unit).

2. Implementation of intelligent navigation systems:
- use of autonomous route planning systems taking into account airfield constraints;
- use of machine learning to predict trajectories and avoid obstacles;
- integration with digital maps of airfield infrastructure.
3. Optimization of design modularity:
- development of unified joints with a minimum turning radius;
- use of lightweight materials to reduce inertia;
- ability to quickly reconfigure the composition to adapt to the conditions.
4. The use of non-standard chassis configurations:
- implementation of omnidirectional wheels (Omni or Mecanum);
- use of tracked or combined chassis to increase cross-country ability;
- development of transformable platforms with the possibility of lateral movement.
5. The implementation of the proposed conceptual framework will allow:
- reduce the time for technical operations on an airfield;
- improve traffic safety in confined spaces;
- reduce the workload on operators through automation;
- increase flexibility and adaptability of ATSEFO to changing operating conditions.

4. Results and Discussion

To ensure autonomy, accuracy, and safety during the maneuvering of modular aerodrome technical support equipment for flight operations during aircraft maintenance, technical solutions based on the interaction of sensor systems with actuators are proposed (Fig. 5), which are development of research involving one of the authors of the article *(Vasylev et al, 2024)*.

The scheme (Fig. 5) is based on the principle of a cyber-physical system: sensors collect information → data are processed → trajectory is planned → actuators realize movement → safety is monitored → feedback.

Structural levels:

1. Information level – GPS, LiDAR, cameras, IMU → forming a picture of the environment.
2. Analytical level – data processing, mapping, localization, and route planning.
3. Control level – PID/MPC controllers, navigation algorithms.
4. Physical level – drives, axles, brakes, modules of a road train.
5. Safety level – safety sensors, stopping mechanisms, all-round cameras.
6. Communication level – CAN-bus, exchange interface with external systems (airfield, operator).

To provide an in-depth description of the structural blocks of the scheme of interaction between sensors and actuators of the modular road train (Fig. 5), we will modify flowchart with a transition from a multilevel approach to a block approach (Fig. 6).

The structural blocks are shown in Fig. 6 and have the following content.

1. Navigation and orientation block:
- purpose: determines the position of the road train on the lane;
- components: GPS module – global localization; IMU – inertial navigation (accelerometer and gyroscope); LiDAR/camera – obstacle detection and area mapping;
- output signals: coordinates (X, Y), orientation (θ), map of the environment.

2. Sensor data processing unit:
- purpose: integrates information from sensors to build a navigation model;

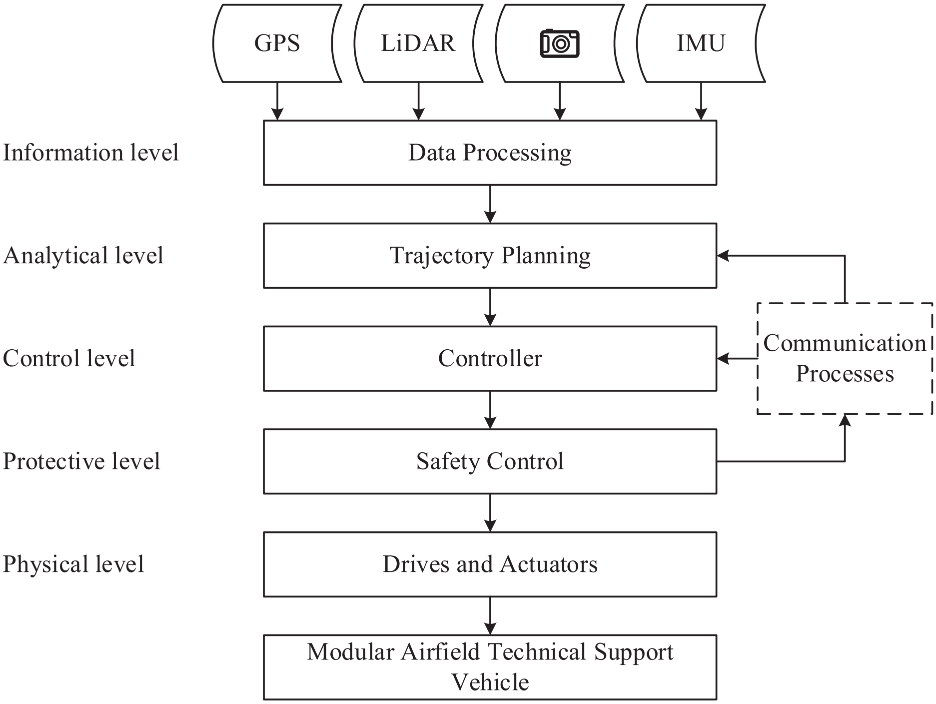

Fig. 5. Scheme of interaction of sensor systems and actuators of a modular aerodrome technical support equipment for flight operations by levels

− components: processor (SoC / FPGA); SLAM or V-SLAM algorithm; communication interface with the control unit;

− function: filtering, merging, localization in real time.

3. Trajectory planning and control unit:

− purpose: determines the optimal route to the service area;

− components: path planning algorithms (A*, Dijkstra, RRT); PID or MPC controllers for motion stabilization; collision prediction model;

− output: movement commands based on safety and efficiency.

4. Drive and actuator unit:

− purpose: performs maneuvering according to control commands;

− components: electric drives on each module; omnidirectional or articulated axes; steering and braking control unit;

− special feature: the ability to independently control each module (for example, a lateral movement mechanism).

5. Safety control unit:

− purpose: Provides protection of the aircraft and ATSEFO itself during maintenance;

− components: zone proximity sensors; surround view cameras; algorithms for stopping in case of danger; interaction with the operator or intelligent system.

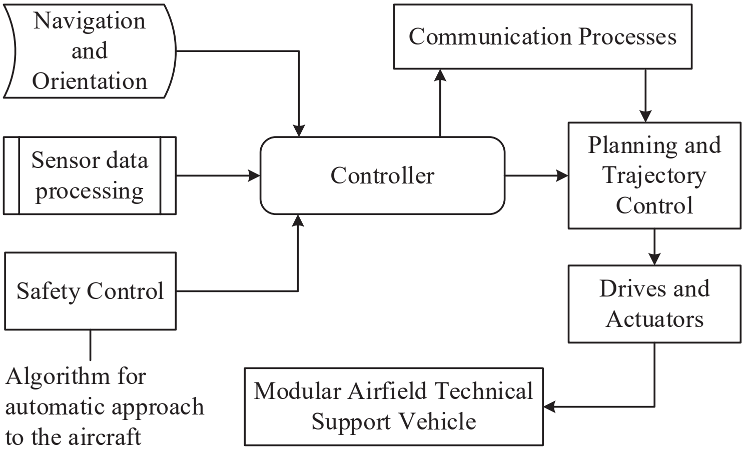

Fig. 6. Modified block diagram of the interaction of sensor systems and actuators of the modular ATSEFO

6. Communication unit:

− purpose: provides communication between the units, as well as between the ATSEFO and the airfield infrastructure;

− components: CAN-bus / EtherCAT / ROS communication; Wi-Fi / 5G / UWB modules for data transmission; interfaces with the ground automated system.

These units form an integrated system that ensures autonomous, safe and accurate maneuvering of aerodrome technical support equipment for flight operations equipment around the aircraft, especially when reversing.

Three scenarios were modeled in the MATLAB Simulink virtual environment: parking, approaching the aircraft, and emergency turnaround. The results showed a reduction in the minimum turning radius from 14.2 m to 9.8 m, as well as a 27% reduction in time to perform the maneuver. The data obtained confirm effectiveness of proposed technical solution.

The effectiveness of modular aerodrome technical support equipment for flight operations is confirmed by a number of international projects, especially in the context of Industry 4.0, automation and increased maneuverability:

1. The Industry 4.0 and Society 5.0 project (Norway – Ukraine) *(Østbø et al, 2022).*

Within the framework of cooperation between the Norwegian University of Science and Technology and Igor Sikorsky Kyiv Polytechnic Institute, a number of resears were implemented on the introduction of digital technologies in production and logistics processes, in particular:

− modular transportation systems were considered as part of digital transformation of airfield infrastructure;

− the effectiveness of intelligent control of mobile platforms in cramped conditions was studied;

− emphasized the role of sensor systems, autonomous control and digital maps in improving accuracy of aircraft maintenance.

2. TLD TractEasy – autonomous towing vehicle (France) *(EasyMile, n.d.), (Ground Handling International, 2023)*.

This modular electric tractor is used at the airports of Lyon, Singapore, and Amsterdam for towing luggage:

− equipped with LiDAR, GPS, cameras and intelligent control;

− operates without a driver, performs towing tasks with high accuracy;

− research has shown an 18-25% reduction in aircraft maintenance time and a reduction in the risk of collisions.

3. Research under the Horizon Europe program *(ALBATROSS Consortium, 2023)*.

ALBATROS aims to improve aviation safety in the face of new risks, including introduction of new types of energy systems and autonomous platforms. As part of the airport digitalization project:

− the efficiency of modular platforms with autonomous control for aircraft maintenance is analyzed;

− it was determined that adaptive modularity allows reducing the number of equipment near the aircraft without losing functionality.

Important aspects of ensuring the effectiveness of modular ATSEFO are compliance with European directives on the overall lane, turning radius and maximum folding angle; use of wheel steering algorithms that take into account the permissible limits of angles and speeds; training of drivers to work with modular road trains, especially when driving in reverse; use of simulators to practice complex maneuvers at the airfield.

5. Conclusions

Improving maneuverability of modular road trains is the critical area of airfield technical support systems development. An integrated approach that combines engineering, information and organizational solutions allows for the creation of efficient, safe and adaptive new generation vehicles.

The integration of modern technical solutions into the design of modular road trains significantly improves their maneuverability in confined spaces and increases the efficiency of airfield technical support. The modeling results indicate a significant potential for improving maneuverability without radically changing the design of a road train. However, the implementation of such solutions requires taking into account limitations in terms of cost, electronics reliability, and peculiarities of operation in conditions of high vibration.

In the future, it is advisable to conduct experimental tests of the developed solutions in real conditions to validate theoretical conclusions, to conduct comprehensive researches that would take into account impact of weather conditions, load, and human factor on maneuverability of modular road trains in aerodrome technical support equipment for flight operations system.

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