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Case Study on the Use of Unmanned Aerial Vehicles for the Maintenance of Ocean Engineering Facilities

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Abstract: The article presents the concept of using innovative unmanned aerial vehicles (UAVs), including autonomous UAV-I for inspection activities, auxiliary and transport works in the processes of servicing large-scale ocean engineering structures in the offshore part of the sea. The proposed areas of application of UAV-I devices and key technologies determining the possibility of using these vehicles in difficult operating conditions at sea are presented. Simulation studies were carried out on the possibility of sequencing maintenance tasks and maintaining the efficiency of technical devices installed in various locations of the mining platform at relatively short time intervals not exceeding 3-4 hours. It was envisaged to use a limited resource of three drones with a specific purpose and functional characteristics. The limitation of the time horizon of the analysis was determined by the specific ranges of drone flights and the time-consuming nature of their operations.

Keywords: aerial vehicles (UAVs), drones, maintenance tasks, offshore structures, simulations, mining platform, sequencing.

1. INTRODUCTION

The wide spectrum of applications of unmanned aerial vehicles (UAVs) is associated with an ever wider range of design solutions and the reduction of costs of their production and operation thanks to the use of modern manufacturing techniques and information technologies (Ukaegbu et al., 2021). UAVs, including drones, can be used, for example, in small and medium size manufacturing companies allowing them to reach logistic agility without major financial outlays (Deja et al., 2020; Zhong et al., 2020, Kumar et al., 2021). UAV-based system for interactive control or large scale metrology applications can be an alternative to human- or robot-based systems used in different manufacturing environments, such as aerospace, automotive, shipbuilding, and railway (Franceschini et al., 2010, Ostanin et al., 2021). Special challenges are faced by designers and manufacturers of small unmanned objects weighing less than two kilograms (Hassanalian & Abdelkefi, 2017).

In addition to many benefits, the use of UAVs is also associated with the threats identified as one of the most current and requiring urgent action and identification. Unmanned aerial vehicles can protect industrial and public facilities against threats. They can also be a source of threats to particularly protected facilities, such as nuclear power plants (Irizarry et al., 2012; Kindfuller et al., 2016). Inspection of marine and coastal areas with drones is advisable due to the high flexibility of their applications (Duan & Zhang, 2014), however, with time constraints related to energy consumption and battery capacity.

Their use also shows promise in assisting the monitoring of gas and oil pipelines as well as offshore wind turbines (Cho et al., 2015; Gómez & Green, 2017; Shafiee et al., 2021). The wide area of application of UAVs indicates that the processes of operating ocean engineering facilities and structures should now be supported by the use of drones.

2. PLANNING THE TECHNICAL MAINTENANCE OF OCEAN ENGINEERING FACILITIES USING UAVs

The basic functions of the technical maintenance process focus on:

- ensuring safe operation of offshore facilities, such as: mining platform, wind farms, and failure-free operation of installed devices enabling proper operation and achievement of quality and efficiency goals;
- ensuring the continuity of work, including minimization of losses resulting from possible failures of technological devices and costs related to their repair through preventive planning of technical service and optimization of its costs;
- maintaining safe working conditions for all devices.

It is assumed that the organization of the maintenance process of individual devices of the facility, including the key ones, operated in particularly difficult environmental conditions, takes into account maintenance activities. aimed at preventing the occurrence of damage, the spread of which may disrupt the basic function of the object or pose a threat to safety. Preventive maintenance (PM) planning involves the definition of the scope of periodic inspections and the determination of their frequency.

Therefore, the process of maintenance of such a complex facility is assumed as the subject of planning, where reliability characteristics should be seen as the basis for its development. These types of characteristics should be created on the basis of operational tests of devices of individual classes, which, as a consequence, will be the input data for the development of a coherent dedicated computer-aided service (CAS) system. In the diagnostics aimed at determining the technical condition of individual offshore structures, the use of the analyzed UAVs is particularly appropriate. As part of the planned activities of technical diagnostics, the following activities were assumed:

Monitoring - i.e. observing and tracking quantitative and qualitative changes in certain physical quantities regarding the technical condition of a device that is a component of the operated object, without affecting this device;

Supervision - related to the processing and sending of information on physical quantities related to the technical condition;

Diagnosis - oriented towards detecting irregularities or increased probability of their occurrence.

The operation of technological elements of the drilling platform can be analyzed using the Failure Mode and Effect Analysis (FMEA) technique or the known Failure Mode and Criticality Analysis (FMCA) method, as well as Fault Tree Analysis (FTA) (Arabian-Hoseynabadi et al., 2010; Shafiee at al., 2021).

The design, construction and operation of innovative unmanned aerial vehicles for inspection UAV-I and auxiliary works, requires precise determination of the purpose of these vehicles already at the concept stage, depending on the anticipated operational tasks.

It was assumed that the anticipated implementation of these facilities depends in turn on the following factors:

- purpose of the object (purpose of works),
- innovation of the proposed solution,
- experience and commitment of teams participating in the implementation,
- decision-making process taking into account the risks associated with the tasks performed in the changing ofshore conditions,
- research and implementation costs.

The aim of the currently conducted works is to develop the design of a multi-purpose UAVs that can be used in the following areas:

- inspection and diagnostic unit UAV-I: a drone for inspection and diagnostics of large-size land facilities and infrastructure, high-rise buildings (skyscrapers), offshore ocean engineering facilities;
- transport unit UAV-T: a drone for carrying out transport works of small elements during assembly and disassembly of equipment for large-size objects;
- working (executive) unit UAV-W: a drone for carrying out auxiliary works, including assembly and disassembly works of sensory instrumentation during the construction and renovation of large-scale facilities and land infrastructure.

3. DESIGN FEATURES AND USE OF UAVs ON AN OFFSHORE OCEAN ENGINEERING FACILITY

For the so-called advanced technologies that are of key importance in the development of the proprietary solution of the UAVs include the following technologies:

- technologies ensuring the autonomy of the UAV understood as a system;
- sensors;
- effectors;
- material technologies;
- technologies of supplying the facility with energy;
- information technology, including control, navigation and communication;
- space and satellite technologies.

The subject of the research are two types of UAV structures. The first structure is designed to perform control and diagnostic tasks, the second one is used to carry out transport operations of small elements with the support of maintenance works.

The designed inspection and diagnostic vehicle UAV-I has the following basic technical parameters:
- overall length: 0.8 m;
- working width: 0.4 m;
- structure height: 0.25 m;
- total weight: 8 - 14 kg, depending on the weight of sensors, sensor-effector subsystems and batteries (power supply system);
- operating speed: 0.1 - 2.0 m/s;
- mission time (depending on the frequency of changing the position and the operating speed of the vehicle): min. 1 hour.

The designed transport vehicle UAV-T has the following basic technical parameters:
- overall length: 1.2 m;
- working width: 0.6 m;
- structure height: 0.3 m;
- total weight: 10 - 22 kg,
- operating speed: 0.2 - 5.0 m/s;
- mission time (depending on the frequency of changing the position and the operating speed of the vehicle): min. 1 hour.

The visualization of the UAV-I and UAV-T vehicles are shown in Figure 1 and Figure 2 respectively.

The use of UAVs during the operation of a given ocean engineering facility is based on the following elements:

- definition of the reference system (Oxyz) in which a given UAV can perform inspection, diagnostic or transport operations;
- definition of the starting point (x_p, y_p, z_p) and end point (x_k, y_k, z_k) of the UAV mission;
- definition of the trajectory of the movement T(x_i, y_i, z_i) of the UAV;
- definition of the nature of the mission of the UAV: inspection, diagnostic, transport;
- equipping the UAV with appropriate operational software enabling the implementation of the mission in the operating mode: under the supervision of the mission operational center (COM) or autonomously.

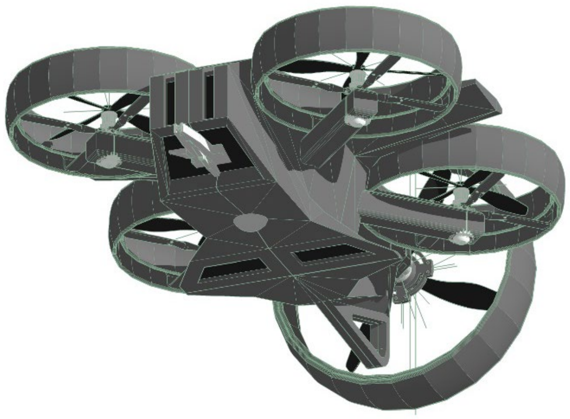

Figure 1. Visualization of the UAV-I in the inspection and diagnostic version.

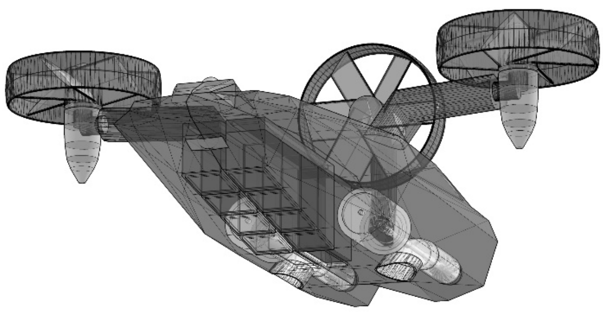

Figure 2. Visualization of the UAV-T in the transport version.

Figure 3 shows the basic elements related to the use of UAVs during the operation of ocean engineering facilities. The origin of the reference system is located in the COM operational center of the mission on the work deck.

The operated ocean engineering objects may be stationary ones, with a limited number of degrees of freedom of movement or freely moving on the sea surface (Gerigk & and Wójtowicz, 2015; Gerigk, 2016; Wilson, 2003). The analyzed object is a semi-submersible platform on which the movement of any UAV-I will take place in the previously defined Oxyz coordinate system, which in turn will move along with the platform on the free surface of the sea. In general, the motion of the platform on the wave should be considered at six degrees of freedom (6DoF). In the case of a suitably ballasted platform, equipped with a Dynamical Positioning (DP) system or dynamically anchored, it is possible, at the concept development stage or at the beginning of the design process, to limit the number of degrees of freedom of the platform movement. Depending on the situation, the movement of the platforms can be analyzed for a smaller number of degrees of freedom, for example for 3 (3DoF) or 4 (4DoF).

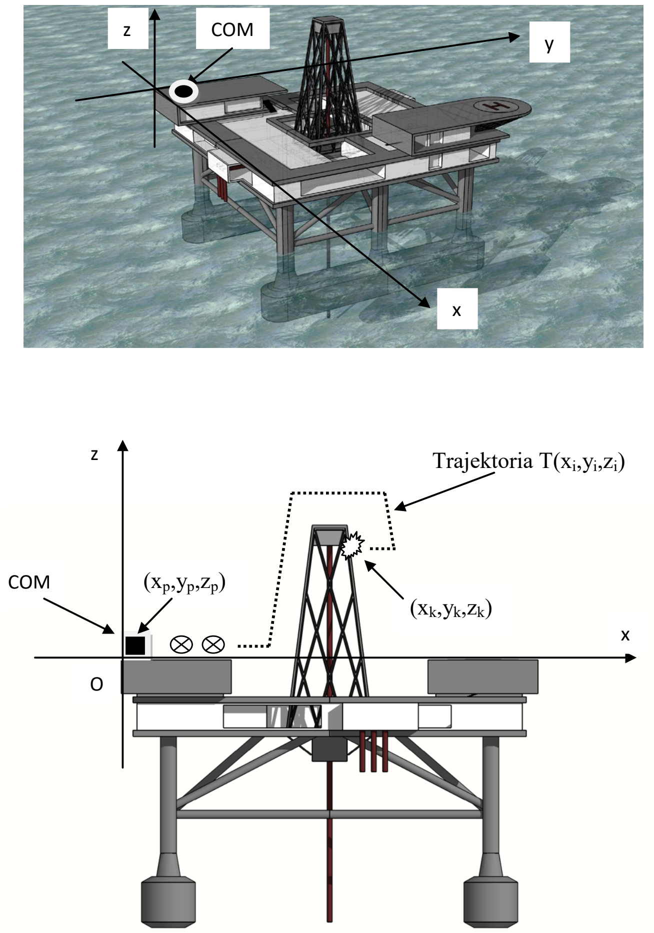

Figure 3. Basic elements of the concept of using UAVs in the maintenance processes of ocean engineering facilities.

4. SCHEDULING UAVs' TASKS FOR MAINTAINING THE OCEAN ENGINEERING FACILITIES

Using UAVs to maintain the efficiency of ocean engineering devices requires defining the tasks that can be performed by them. The use of computer systems for scheduling the analyzed processes enables their visualization, simplifies and improves control over their implementation. It allows for better use of drones and performing scheduled tasks on time (Olivares et al., 2015; Preactor APS®, 2011).

Constraints for resources and tasks can be easily identified and managed. For the available resources, lists of tasks to be performed can be quickly generated to best balance the execution capabilities of UAVs.

For the analyzed ocean engineering object, an operational structure was adopted, consisting of the operational center of the mission (COM) and *n* Task$_{m,n}$ in specific *m* OM$_n$ locations - Figure 4.

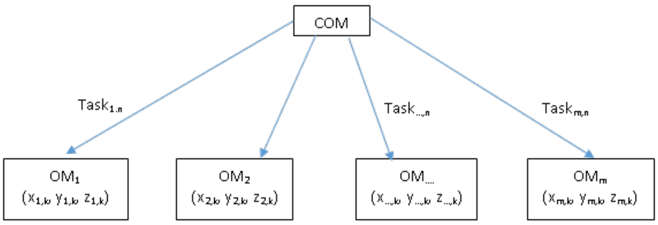

Figure 4. Operational structure of maintenance processes for the monitored objects OM_m of ocean engineering facilities.

The following classification of maintenance tasks types was adopted, hereinafter referred to as: $n = 1, ..., 6$, and carried out by Dd drones on the monitored object OM_m located at m:

$Task_{m,1}$ – inspection of the object monitored with the use of an inspection drone D_1;
$Task_{m,2}$ – diagnostics of the object monitored using a diagnostic drone D_2;
$Task_{m,3}$ – inspection and diagnostics of the object monitored with the use of the inspection D_1 and diagnostic D_2 drones;
$Task_{m,4}$ – repair of the monitored object using a transport drone D_3;
$Task_{m,5}$ – diagnostics and repair of the object monitored using the diagnostic D_2 and transport D_3 drones;
$Task_{m,6}$ – inspection, diagnostics and repair of the object monitored using the inspection D_1, diagnostic D_2 and transport D_3 drones.

An operating scheme of the engineering facility shown in Figure 5 was suggested as a testbed. The travel routes of individual UAVs used for related logistics and maintenance tasks are implemented in a star-type arrangement, typical for for cellurar manufacturing in the industry (Wemmerlöv and Hyer, 1989). In order to avoid possible collisions, movements of drones to and from the monitored objects are carried out in defined vertical planes, however, at two different altitudes (US Patent Application Publication, 2017). Similarly as in tasks concerning planning the structures of FMSs, the flexibility of the layout under consideration can be defined in the following form (Siemiatkowski & Vargovská 2019):

$$\varphi(L_i) = \frac{\sum_{j=1}^{m} \gamma_j}{m} \tag{1}$$

where γ_j might be given by:

$$\gamma_j = -\sum_{k \neq j}^{m} \rho_{jk} \log(\rho_{jk}) \tag{2}$$

as far as using the notion of the informational entropy is assumed, and with

$$\rho_{jk} = \frac{1/d_{jk}}{\sum_{k \neq j}^{m_0} 1/d_{jk}} \tag{3}$$

where d_{jk} is the distance between machine j and k, and m is the total number of monitored objects (resources) in an engineering facility.

The parameter ρ_{jk} measures the relative ease with which object k can be accessed from the fixed object j., viz. COM. The function γ_j expresses the load handling flexibility from the location j (UAVs parking lot) to the monitored object and back. The following can be particularly noted in regard to such a formulation:

- γ_j increases with decreases in the differences of distances between individual objects and is maximum ($\gamma_{jmax} = \log(m - 1)$), when $\rho_{j1} = \rho_{j2} = ... = \rho_{jm} = 1/(m - 1)$ (i.e. flexibility at resource location j is maximum when all other facility resources are equidistant),
- γ_j value increases with the increase in the number of accessible objects from given object location j, when $\rho_{j1} = \rho_{j2} = ... = \rho_{jm}$.

At the same time, scheduling was based on the assumption that only one drone can perform the task at one location D_d. The algorithm assumes that two different subtasks $Task_{m1,n1}$ and $Task_{m2,n2}$ can be performed simultaneously by the drone D_{d1} assigned to $Task_{m1,n1}$ and the drone D_{d2} to $Task_{m2,n2}$, provided that $m_1 \neq m_2$ oraz $d_1 \neq d_2$. If both conditions are not met, the start of one of the subtasks is shifted until the end of the second subtask.

In the analysed case study, the following tasks were assumed to be accomplished:
$Task_{1,6}$ – task type no. 6 in location 1;
$Task_{2,6}$ – task type no. 6 in location 2;
$Task_{3,1}$ – task type no. 1 in location 3;
$Task_{3,2}$ – task type no. 2 in location 3;
$Task_{4,1}$ – task type no. 1 in location 4;
$Task_{4,5}$ – task type no. 5 in location 4.

The possibilities of sequencing maintenance tasks and maintaining the efficiency of technical devices installed in various locations of the mining platform in relatively short time intervals, not exceeding 3-4 hours, were simulated. It is also planned to use a limited resource of three drones, with the above-mentioned purpose and functional features (characteristics). The limitation of the time horizon of the analysis was determined by the specific flight ranges of the drones and the time-consuming nature of their (dedicated) maintenance operations. The task of prototyping operating schedules was carried out in the environment of the Preactor APS® computer application (Preactor APS®, 2011). The individual maintenance tasks included in the illustrative application case study were dedicated to specific machine resources (here adequately equipped drones) by planning their runs in the form of orders for specific locations (according to the physical location of the supported technological devices), as a sequence of task types defined within the created relational database of realised tasks. A formalized order coding scheme was adopted as Lx-z, where consequently: x – is the location number, and z – is the designated task type on the notification list, in accordance with the generated scenarios of equipment maintenance. Figure 6 shows the automatically generated variant of the operational schedule in the form of a

Gantt chart for the scenario layout and the corresponding maintenance and service tasks of the mining platform system. The scheduling of tasks according to the FIFO (First in First out) heuristics was assumed for the established number and forecast frequency of preventive maintenance activities as well as the unforeseen repairs.

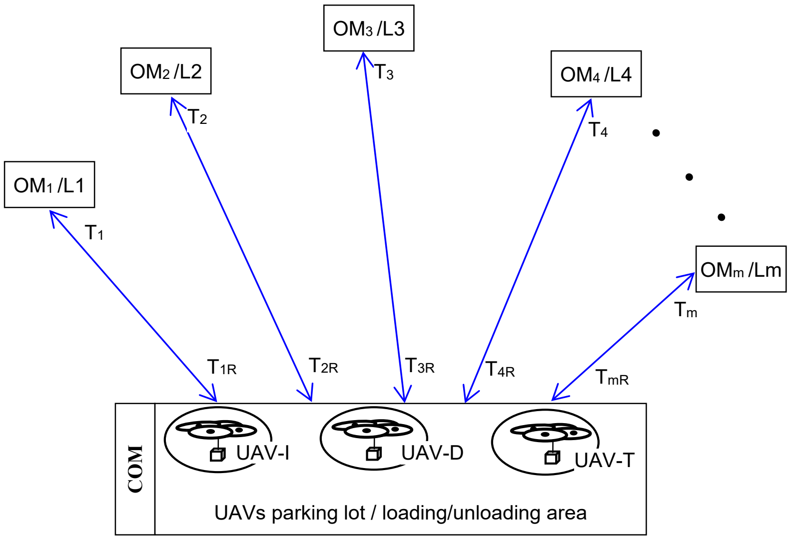

Figure 5. Schematic layout configuration of the ocean engineering facility with itineraries of respective UAVs applied to related logistics and maintenance tasks; T_1, … T_m – tracks to a definite location (at 1st altitude), T_{1R}, … T_{mR} –corresponding return tracks (at 2nd altitude).

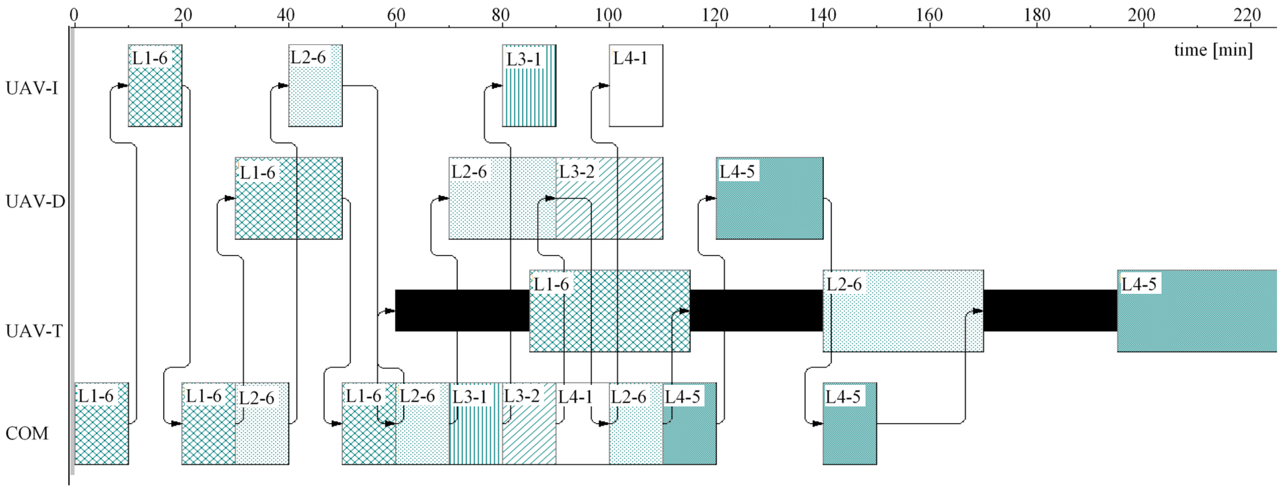

Figure 6. Draft operational schedule for the implementation of maintenance tasks on the offshore platform carried out with the use of UAV in a specific time horizon, generated in the Preactor APS® software environment; black shaded blocks for UAV-T are concerned with its setup.

5. CONCLUSIONS

The wide and intensively increasing area of UAVs use indicates that the processes of ocean engineering facilities should now be supported by the use of drones with dedicated design and equipment. Energy, equipment and human resource constraints force supporting the scheduling of maintenance works, as shown on the example of a mining platform equipped with a task service centre for three UAVs.

It is purposeful and possible to optimize the scheduling (sequencing) of the course of maintenance tasks in various locations, especially for a set of platforms or wind farms, with the use of UAVs for specific scenarios in the conditions of a large number of incoming requests for maintenance tasks. This is effectively possible thanks to the Advanced Planning & Scheduling strategies (APS®) implemented in commercial systems.

The process of technical maintenance of such a complex object as an mining platforms requires behaviour recognition and development of reliability characteristics of the exploited technological devices operating in difficult sea conditions. These types of characteristics should be created on the basis of operational tests of specific classes of devices, which, in consequence, will be the input data for the development of a coherent dedicated CAS system (computer-aided servicing) and the development of adequate CAT systems (computer - aided testing).

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