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# State of the Art Technologies Used as a Rescue Response During Recovery from Structural Collapse

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**Abstract.** This paper is a description of the state of the art technical equipment procured during the execution of the project "Innovative solutions for stabilizing building and engineering structures as a rescue response during structural collapse recovery". The project is financed by the National Centre for Research with an execution frame of 2015 to 2017, and carried out by the consortium of the Main School of Fire Service in Warsaw, The Fire Service College of the State Fire Service in Kraków, the Scientific and Research Centre for Fire Protection – National Research Institute and CMGI Sp. z o.o. The technical specifications are presented for an unmanned air vehicle (UAV) built on commission for the Main School of Fire Service; the UAV can be used to monitor rescue mission operations at the sites of collapsed building.
**Keywords:** automation and robotics, building collapse, fire service, mobile robot, UAV

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## 1. INTRODUCTION

Emergency management operations cannot be fully automated, unlike manufacturing operations; human intelligence, foresight and making the best informed decisions about the problems to hand cannot be managed by any mechatronic device. However, robots can perform some tasks much more efficiently and precisely than humans, who, under the high pressure of time, would risk their health and lives. The use of unmanned vehicles, which are generally operated remotely by humans, provides a safer alternative under these conditions. Mobile robots can assist in emergencies and save precious time by monitoring the vicinity of an emergency event; for example, a robot can undertake highly professional testing of water (e.g. by measuring pH values) or air (e.g. by testing the concentration levels of aromatic hydrocarbons).

Emergency or crisis management is a field of responsibility for the official authorities at various levels of the hierarchy, from the top and central one to the local one. The emergency management system in Poland includes operating services: emergency responders, the Police, the State Fire Service, the Volunteer Fire Service, the Forest Guard, the Border Guard, and various official inspection authorities, such as the Environmental Protection Inspectorates, the Building Engineering Supervision Service, the Veterinary Inspectorates, and the State Sanitary Inspectorate. According to the current functional principles of the Polish emergency management system, these operators function during the emergency prevention, preparation and response stages (the rebuilding after an emergency disaster recovery is not part of their mission).

The purpose of emergency management is to prevent emergencies, build preparedness to control emergencies by planned action, respond to actual emergencies, and to recover or restore the original condition of infrastructure which has failed due to the emergency. Emergency management is an organisational and functional system essential for the effective assurance of safety for people during situations hazardous to life, property and the environment; hence emergency management should include all levels of state management. In the era of developing democracies, one of the more critical functions of any modern state is to provide national citizens with basic protection against potential and actual threats.

This mission of state administration, services and inspectorates should be adequate to the changing landscape of threats and the development of civilization. Effective and efficient emergency management needs to use and benefit from technological progress and innovation. Technological progress and innovation extend the abilities of services to prevent hazards and to contain the effects of any emergency. Official decision-makers must consider the current demands, budgets and the capabilities of technology in emergency management.

Emergency response missions tackle hazards which expose the lives of many to risks. It is essential then to employ the available emergency forces and resources (including financial assets) in the best way possible to assure the most effective and safe conditions for rescue operations, where the safety of the emergency responders is a top priority. The operating effectiveness of emergency responders is critical to human health and life; therefore it is critical to assure the safety of services during natural disasters (floods and earthquakes) and engineering disasters related to the activity of man (which includes rail and road disasters, chemical spills, etc.).

Emergency management teams usually need to face disastrous and dramatic conditions that require critical decision-making in very little time. These conditions make it difficult to gain complete insight and analyse the emergency situation, especially when the emergency services respond to a large emergency in an unknown area. Under these conditions, emergency management teams operate first by focusing the efforts and assets on securing the emergency site and containing the source of the emergency (e.g. a building on fire or a chemical tanker overturned on a road), and their focus on the potential vectors of adverse developments and the prevention of the consequences thereof come second, depending on the staff count and the severity of the emergency at hand. The emergency management operations focus on the actual emergency site and its direct vicinity (e.g. by investigating the conditions in adjacent buildings in the case of a natural gas leak), which greatly extends the scope and efforts of emergency response. Equipment and state of the art technologies in the areas of robotics, aerospace, ICT, and materials engineering can be very helpful to human emergency managers and responders [1].

## 2. EMERGENCY RESPONSE TECHNICAL PLATFORM

### 2.1. Applications of the PIAP SCOUT®

Figure 1 shows the PIAP SCOUT®, a small reconnaissance robot [2]. The PIAP SCOUT® (Fig. 1) is a robot unit intended for the rapid reconnaissance of land and inaccessible locations. The modular architecture of this robot allows it to serve as a mobile technical platform for the inspection of flooded vehicles and confined spaces. With an optional manipulator installed, the robot can handle objects weighing up to 5 kg. The distinguishing features of the robot are its high manoeuvrability and high travel velocity (7 km/h). The propulsion units of the robot allow it to easily negotiate irregularities in the terrain and obstacles with an inclination angle of up to 45°. The wheels of the robot are easily removed to reduce its footprint in storage. The light weight and compact size of the robot facilitate shipping and handling: the robot can be carried in a backpack.

Fig. 1. PIAP SCOUT®, a small reconnaissance robot

The robot has 4 cameras with IR LED lamps, which can be replaced with visible-light LED lamps for missions under various lighting conditions. The optional optical fibre feed allows use of the robot in areas with high electromagnetic interference. The PIAP SCOUT® robot can operate a large variety of optional accessories. These include rocket projectile launchers (e.g. Chemring RE 70M3 and Proparms Recoilless 12.5 mm or 20 mm), automatic shotguns (e.g. Benelli models), a radiographic camera, an explosive material vapour sensor, a chemical contamination sensor, an active winding reel for an optical fibre cable, or a remote explosive detonator [2].

## 2.2. Features of the PIAP SCOUT®

The PIAP SCOUT® robot has design features (including whip-styled flexible antennas) that allow it to navigate through confined and hard to reach spaces, including sewers, drainage systems, and similar. The optional multifunctional manipulator can have the lower arm adjusted manually as needed and equipped with the hardware required by the mission specifics, weather, or time of day (the optional hardware for the manipulator includes a recoilless projectile launcher, an additional visible light camera and a night vision camera). The manipulator and the camera pod are installed on gimbals for angular adjustment The manipulator makes the robot very useful in handling objects weighing up to 2.5 kg (with the manipulator fully extended) or 5 kg (with the manipulator fully retracted).

The robot outputs a video feed from a full-colour varifocal PTZ camera with 22x optical zoom and optional IR LED lamps or visible light LED lamps. The PTZ camera range of motion is 350° in pan and 150° in tilt. The remote operator's console allows full interaction with the robot controls and optional accessories. The robot system has been designed to keep the remote operator fully mobile; hence the remote operator's console is installed in a PELI case with a 15" LCD TFT display and an exchangeable battery pack (which is identical to the battery pack of the robot) [2].

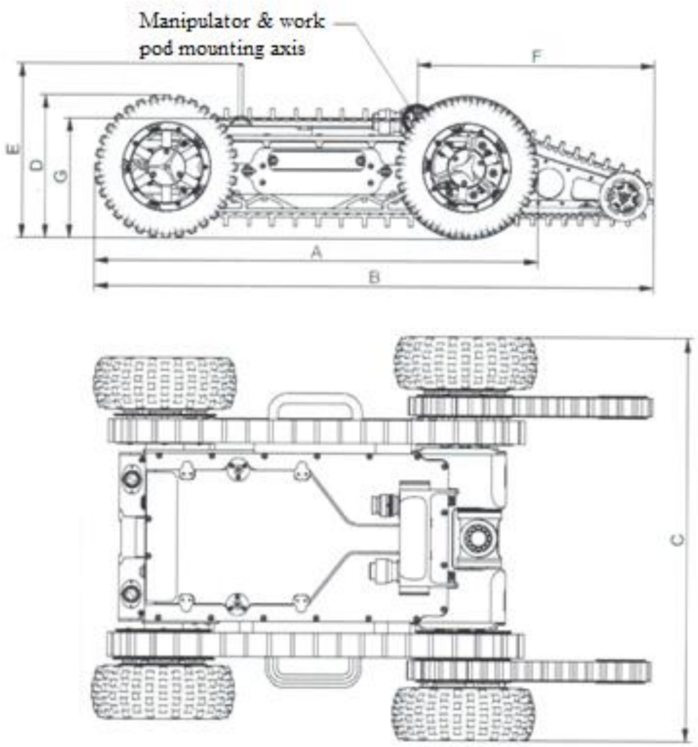
## 2.3. Dimensions of the PIAP SCOUT®

Figures 2 to 4 show the basic dimensions of the robot's mobile platform [2]. A commercially available counterpart of the robot is the PackBot Scout. Similar in design to the PIAP, the Scout is the basic version of this robot mobile platform. The robot's mobile platform can carry five different accessories, depending on the mission requirements. The robot's structure is robust enough to fully withstand a fall from 1.83 m onto a concrete surface. The PackBot Scout, the dimensions of which are similar to that of the PIAP SCOUT®, weighs approximately 18 kg with all accessories installed and is 20 cm high.

The version designed for exploration of collapsed building rubble is the PackBot Explorer. The PackBot Explorer can provide a video feed from the search and rescue area, over and under the obstacles, while the manipulator can handle debris. The PackBot Explorer's camera pod features multiple lenses, laser pointers, motion sensors, microphones, and other hardware. The PackBot Explorer was used to search the remains of the WTC towers on 11/09/2001, to find survivors, and to output images for assessing the structural integrity of the remaining buildings in the WTC complex.

One example of the application of a full spectrum of existing unmanned land vehicles is the emergency response mission in the city of Sendai, Japan, which was damaged during an earthquake in March of 2011. This mission included the following mobile platforms:

– Snakebot, designed and built at Tohoku University (the mobile platform mimics the movement of a live snake and features a wireless video camera);
– Quince crawler robot, developed by the Future Robotics Technology Center at the Chiba Institute of Technology (this mobile platform weighs 26.4 kg, can move at a maximum speed of 1.6 m/s, and can use a $CO_2$ detector and an IR camera).

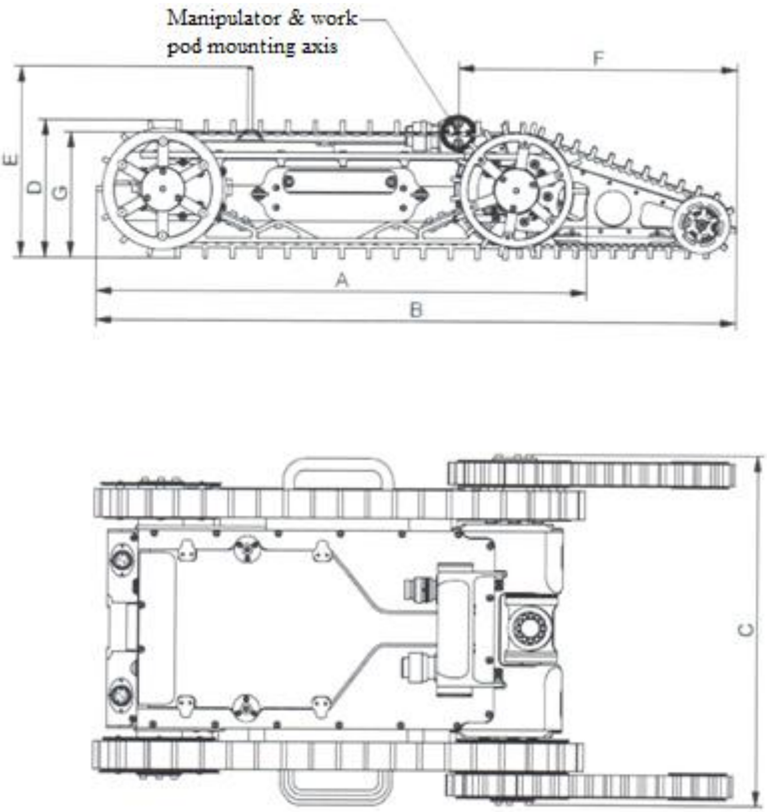



| Dimension | Designation | Size |
|---|---|---|
| A | Length with front tracks withdrawn | 60 cm |
| B | Length with front tracks deployed | 75 cm |
| C | Width | 54 cm |
| D | Height | 19 cm |
| E | Height with maximum deflection of whip antenna | 21 cm |
| F, G | Manipulator mount axis location | 31 cm, 15 cm |

Fig. 2. Dimensions of the PIAP SCOUT® with land wheels

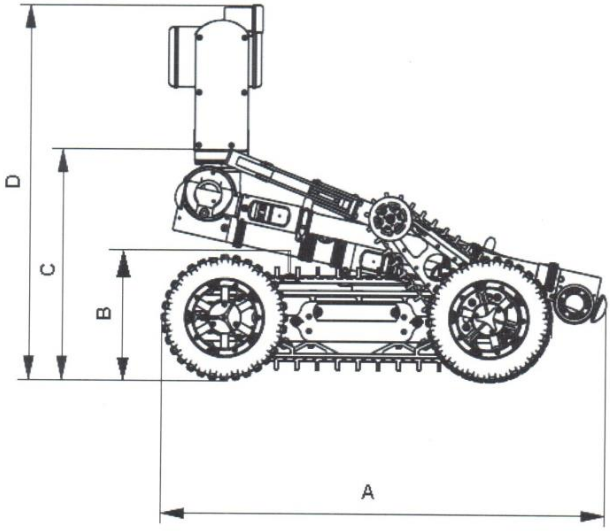
Another emergency response mission where robots were essential for the safety of the emergency responders was the recovery from the TEPCO nuclear power plant disaster in Fukushima, Japan. The following technical platforms were used on site:

– Monirobo monitoring crawler robots (the mission configuration at the time included manipulators for clearing obstructions, a sensor package, a 3D imaging camera, a Geiger counter, and dust sampling implements);
– PackBot 510 EOD (explosive ordinance disposal) unit;
– Warrior 710 heavy crawler robot (which can navigate rubble and stairs while handling objects weighing up to 100 kg);
– a number of different firefighting robots from Japan and Australia [3].




| Dimension | Designation | Size |
|---|---|---|
| A | Length with front tracks withdrawn | 56 cm |
| B | Length with front tracks deployed | 74 cm |
| C | Width | 40 cm |
| D | Height | 18 cm |
| E | Height with maximum deflection of antenna whips | 20 cm |
| F, G | Manipulator mount axis location | 31 cm, 14 cm |

Fig. 3. Dimensions of the PIAP SCOUT® without land wheels




| Dimension | Designation | Size |
|---|---|---|
| A | Length | 67 cm |
| B | Height with maximum deflection of outer antenna whips | 21 cm |
| C | Height to the highest part of the retracted manipulator | 33 cm |
| D | Height to the top surface of the main camera pod | 57 cm |

Fig. 4. Dimensions of the PIAP SCOUT® in fully retracted mode

## 3. LEICA STRUCTURAL MONITORING SYSTEM

Measuring the displacement and deformation of structures is essential during recovery operations after a structural or building collapse to assure the safety of the emergency responders operating on site. A structural monitoring system is intended to assure the safety of the emergency responders operating in the area of a direct hazard following a building collapse. The benefits of a structural monitoring system include:

1. The measurement and analysis of structural displacement and deformation is displayed in real time on a work station monitor.
2. The structural monitoring system allows the monitoring of several structural walls at the same time, from a single location.

Figure 5 shows an overview of an electronic tacheometer [4]. An unmanned mobile technical platform is to be interfaced with a 3D laser scanner, but it cannot carry it due to capacity constraints.

In order to meet the basic design conditions (an innovative stability system), the unmanned mobile technical platform should first allow monitoring of the stability of a structure (or its components) which has become unstable due to a disastrous event or a building collapse event. Ideally the unmanned mobile technical platform should be interfaced with a 3D laser scanning system.

The 3D laser scanning system comprises an electronic tacheometer with 3D laser scanning capability and suitable operating system software. The desired structural monitoring system should be able to detect any displacement of the monitored objects in all planes and structural deformations.

Fig. 5. Leica electronic tacheometer

Given that it is not possible to install the electronic tacheometer directly on the unmanned mobile technical platform, and the need to interface the 3D laser scanning system with the platform, the following solutions are proposed:

1. Option I. The electronic tacheometer is deployed on a tripod located in a safe area to monitor the stability of a structure. Whenever the 3D laser scanning system detects the displacement or deformation (an instability) of any structural component being monitored, the unmanned mobile technical platform, equipped with visible light or IR cameras, can be dispatched to do a detailed reconnaissance of those structural components instead of human emergency responders.

   The integration of the data output by the 3D laser scanning system with the data output by the unmanned mobile technical platform can help in making informed decisions on how to secure the unstable structural components.

   The electronic tacheometer can scan the structure to provide a 3D model to analyse the layout of the collapsed building rubble with reference to the video feed from the site. This can help study and evaluate the structure's condition without having to dispatch any human responder for a visual inspection of the hazardous area. The structure can be scanned into a 3D model by deploying the electronic tacheometer in selected locations to achieve full coverage.

The entire operation of scanning and video monitoring with the unmanned mobile platform can be managed remotely (in a command and control vehicle).

2. Option II. The electronic tacheometer is deployed on a tripod located in a safe area to monitor the stability of a structure. The unmanned mobile technical platform monitors the behaviour of the props used to secure unstable structural components (floor slabs or walls) with visible light cameras and microphones. Whenever the unmanned mobile technical platform detects the props beginning to transfer new loads, the mission commander can decide to abort the emergency response within the area of imminent structural collapse where the props have been deployed.
3. Option III. The unmanned mobile technical platform is a point of reference for the electronic tacheometer. The GPS module installed in the unmanned mobile technical platform allows monitoring of the coordinate system with the data output for a continuous determination of spatial points by GPS measurement. The points of reference can only be determined under two conditions: to verify which objects are displaced if the objects are in the field of view of both the electronic tacheometer and the unmanned mobile technical platform, and to determine the points of reference which are beyond the FOV of the electronic tacheometer and which could have a significant impact on the stability of the monitored structure. In the latter case, the software of the electronic tacheometer can generate a virtual point of reference to be monitored by the GPS system installed on the unmanned mobile technical platform. The measurement error of the electronic tacheometer depends on the distance from the monitored object. The point of reference established on the unmanned mobile technical platform and verified by the GPS system has an elevation of 3 cm above the ground level [5]. A concept of the integration discussed here is shown in Fig. 6 [6].

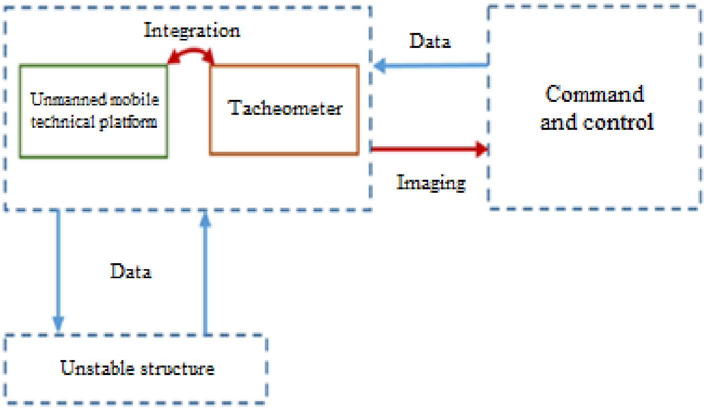



Fig. 6. Unmanned mobile technical platform integration concept

The architecture of the unmanned mobile technical platform subsystem is shown in Fig. 7 [6].

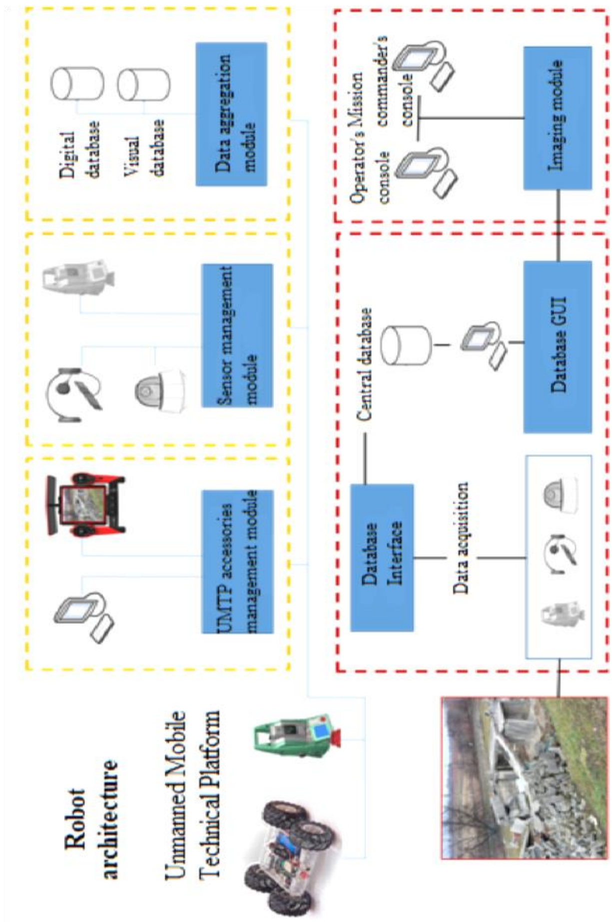



Fig. 7. Architecture of the unmanned mobile technical platform subsystem

## 4. FIELD TESTING THE SYSTEM UNDER SIMULATED OPERATING CONDITIONS

Functional testing of the unmanned mobile technical platform (UMTP) was completed during the research described here. Aside from the research consortium representatives, the field tests were attended by a Leica Geosystems representative and a representative of the ŁÓDŹ Special SAR Group.

The field tests were intended to validate the design conditions for the functionalities, structure, UMTP sensor packages installed, UMTP mobility, UMTP movement types, and the feasibility of using external sensors operated by SAR teams during response at collapsed building rubble sites.

The scope of field tests included:

a) Live functional testing of the UMTP;
b) Testing of the data feed relay from the UMTP systems to the command and control centre;
c) Evaluation of 3D laser scanning accuracy;
d) Intercom system tests;
e) Remote control range testing;
f) Testing the output of readings from an external instrument installed in the UMTP manipulator gripper (a multi-gas sensor);
g) Navigation in specific terrain conditions: in rubble, on paved and level ground, on unsurfaced ground, and in tunnels.

The field tests were carried out at a testing ground in Nowy Sącz, Poland, a facility with purpose-designed building rubble that simulates a collapsed building site (Fig. 8).

Fig. 8. Testing the PIAP SCOUT UMTP in rubble

During the two days of field testing (conducted at the testing ground of the School of Fire Officers in Nowy Sącz) under various terrain conditions and according to various scenarios, the following conclusions were made:

1. The purchased and tested UMTP largely met the criteria and design conditions established in earlier stages of the project.

2. The UMTP exceeded the maximum deadweight established in the design conditions. Still, the UMTP can be handled by one or two emergency responders. A benefit of the exceeded weight limits is the capability of installing a manipulator unit on the UMTP, which is essential for handling small objects and helps the UMTP navigate the terrain.
3. The tested UMTP, the PIAP SCOUT, can be utilized as a reconnaissance module or a direct support platform for emergency responders and firemen at the sites of collapsed buildings.
4. The UMTP has a defined capability for navigating rough terrain, whereas the weight and dimensions of the UMTP facilitate efficient handling by the emergency responders on site.
5. The UMTP can carry small, light-weight equipment, including geophones, multigas sensors, and small implements. This capability allows the extended identification of hazards and better response on site.
6. The PIAP SCOUT cameras allowed reading of the instruments carried by the UMTP's manipulator.
7. The verified remote data and control communication range of the operator's console was approximately 150 m, but which may vary if obstacles are present. The actual remote data and control communication range depends on the density and number of RF communication obstacles. The maximum operating range of the UMTP was largely overestimated from the technical data published by the manufacturer.
8. The application of the manipulator allows the UMTP to handle small objects in rough and confined areas that are, for some reason, hazardous to human responders.
9. The mobility of the UMTP allows it to operate in areas of imminent hazard to human health and/or life.
10. The PIAP SCOUT UMTP also met the project design criteria for chemicals, humidity and operating temperatures, as specified in the relevant technical data sheets of from the manufacturer.

## 5. HCOPTER 4M1315 MULTIROTOR UAV

In 2015, the HCopter 4M1315 multirotor UAV was built on commission from the Main School of Fire Service (see Fig. 9). The UAV is based on the popular Pixhawk flight controller.

Fig. 9. Hcopter 4M1315 multirotor UAV

Technical specifications:
- Take-off weight: 3900 g
- Recommended take-off weight: 4000 g
- Maximum take-off weight: 5900 g
- Dimensions: 660 × 600 mm, height = 290 mm (930 × 910 mm with rotors)
- Maximum operating speed: 20 m/s (72 km/h)
- Flight time: approx. 30 minutes on one battery pack (may vary with flight and weather conditions)
- RF link range: 1.5 km max, may vary with terrain form and obstacles
- Maximum recommended flight altitude: 1000 m

Operating environment limits:
- Ambient temperature: -5°C to +35°C
- Wind speed: max 12 m/s
- No rain or snow (no waterproof rating)

Standard equipment:
- Sony GoPro3+ HD camera with live feed and recording
- Safety-latched drone startup control
- GPS
- Altimeter (barometer-based)
- Heading sensor (magnetometer-based)
- Control instruments, including battery voltage monitoring and output

The UAV also features an RTH (Return to Home) functionality and assisted flight modes, e.g. Course Lock, which, when enabled, causes the UAV to follow a direction preset by the operator irrespective of the orientation of the UAV. The primary mission of the UAV is to enable emergency managers (mission controllers) to monitor the emergency response site.

The UAV is capable of reconnoitring water and land surfaces, irrespective of terrain configuration.

A hazard inherent to flight operations of every UAV is the risk of equipment failure, which usually ends with the UAV crashing into the ground from a considerable height. The most common causes of UAV failures include:

- Loss of RF link with the remote control console
- GPS interruption
- Loss of power (by battery drainage below the minimum voltage due to operator error)
- On-board electronic and/or propulsion failure
- Lithium-polymer battery pack failure. Lithium, when exposed simultaneously to oxygen in the air and water, burns violently at more than 1000°C.

The predicted development directions of UAVs for emergency response operations entail the following on-board equipment suites:

- Thermal imaging and IR cameras
- Cellphone locators
- Hazardous gas and vapour sensors
- Pyrometers [7].

## 6. CONCLUSION

The field testing of the PIAP SCOUT UMTP revealed some discrepancies between the initial project design conditions expected from the UMTP and the actual critical performance characteristics of the UMTP. The tested UMTP unit exceeded the expected deadweight value. Still, the UMTP can be handled by one or two emergency responders.

A benefit of the exceeded weight limits is the capability of installing a manipulator unit on the UMTP, which is essential for handling small objects and helps the UMTP navigate rough terrain, such as staircases. A drawback of the UMTP is that it cannot carry and deploy structural props or the electronic tacheometer, a part of the Leica structural monitoring system. Both tasks will have to be handled by a more capable robot.

The remote data and control communication range of the operator's console is approximately 150 m or less, if RF obstacles are present in the operating theatre of the UMTP. This is far less than specified in the manufacturer's technical data sheets for the UMTP.

During operation in piping systems, such as sewers, drainage ducts, etc., the UMTP's RF communication module fails to meet the initial project design conditions. The inability of routing the RF control and data systems exchanged between the UMTP and its operator's console means the communication technology must be changed.

This paper suggests that unmanned mobile technical platforms can be successfully used in building collapse rescue and recovery operations where the human responders' capabilities are limited. A land robot can navigate collapsed structures and obstacles, while monitoring the site and investigating the extent of the structural damage. The mission objectives of an UAV include monitoring of the emergency response sites by the emergency management centre and reconnaissance of difficult terrain.

The robots contemplated here are unmanned vehicles remotely controlled by a command and control centre (or emergency management mission centre) outside the hazardous area (i.e. a collapsed building). This method of operation helps avoid exposure of the State Fire Service operators to health and life hazards.

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# Nowoczesne technologie stosowane w działaniach ratowniczych podczas likwidacji skutków katastrofy budowlanej

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**Streszczenie.** W artykule przedstawiono opis nowoczesnego sprzętu zakupionego w związku z realizacją projektu „Innowacyjne rozwiązania metod stabilizowania konstrukcji budowlanych i technologicznych w warunkach działań ratowniczych podczas likwidacji skutków katastrofy budowlanej". Projekt finansowany przez NCBR realizowany jest w latach 2015-2017 w ramach konsorcjum: Szkoła Główna Służby Pożarniczej w Warszawie, Szkoła Aspirantów PSP w Krakowie, Centrum Naukowo-Badawcze Ochrony Przeciwpożarowej im. Józefa Tuliszkowskiego – PIB, CMGI Sp. z o.o. Zaprezentowano również dane techniczne bezzałogowego statku powietrznego zbudowanego na zamówienie SGSP, który może zostać wykorzystany do obserwacji terenu działań na gruzowisku.

**Słowa kluczowe:** automatyka i robotyka, katastrofy budowlane, straż pożarna, robot mobilny, bezzałogowy statek powietrzny