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Minimum viable product: A robot solution to EOD operations

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Abstract
This paper presents design and development of EOD robot, with MVP characteristics. The design is based on a solid base structure with arm manipulator attached to the base. The overall dimensions of the robot are 590x860x340 mm and it weighs 55 kg. The robot is capable of towing heavy objects as well as lifting sensitive objects. The robot has a maximum horizontal reach of 1400 mm and a vertical of 1200 mm. The robot is tested according to guidelines developed in the USA, as much as the conditions allowed. Briefly, the results can be summarized as follows: the setup time for the robot is 10 minutes, it can reach speeds up to 8 km/h, it has a towing capacity of 40 kg and the maximum communication reach is 20 m. Among successful tests, the weaknesses were also found which act as a guide for future designs and developments. These weaknesses are what MVP concepts are actually developed for.

Keywords: Explosive ordnance disposal, EOD robot, Ordnance, Robot testing, Minimum viable product, MVP

1. Introduction

Landmine and Cluster munition monitor reported that around 26 states and 3 other areas are contaminated by Cluster munition remnants, as of August 2021 [1]. Cluster munition remnants are defined, by the Convention on Cluster munition, as conventional munition designed to disperse explosive submunitions, weighing less than 20 kg and including that submunition, that failed to detonate [2]. It is very easy to conclude that the impact is still widely present and it is being addressed by many organizations, international as well as national. In Bosnia and Herzegovina, among the countries most hit by cluster munition and landmine contamination, the problem is still being addressed, as the country asked for the extension of the deadline for clearance in 2021 and expects clearance to be completed by late 2022 [1].

There is one more problem authors found. The defense industry companies, locally, are testing explosives at their premises and after an unsuccessful testing usually the human operator dismantles the explosive by hand which can lead to severe injuries, not uncommon to occur in these companies. This and the facts mentioned in the first paragraph, are what inspired and motivated the authors to try to contribute to a solution.

The solution, as seen by the authors, is a remotely controlled robot that is equipped with a manipulator and a gripper and capable of handling operations that are required in an Explosive Ordnance Disposal (EOD). Since EOD robots are readily available on the market, some of the most popular are presented in Table 1.

Table 1. EOD robots available on the market

	Company	Model	Max. lift capacity	Weight	Reach (Forward)	Speed	Reference
1.	Telerob, Germany	tEODor EVO	100 kg	383 kg	1860 mm	3 km/h	[3]
2.	Northrop Grumman, U.S.A.	Andros F6A	61 kg	220 kg	1440 mm	4.8 km/h	[4]
3.	QinetiQ Inc., U.S.A.	TALON	68 kg	81 kg	1570 mm	N/A	[5]
4.	L3Harris Technologies, U.S.A.	T7	113+ kg	322 kg	2200 mm	8+ km/h	[6]
5.	SuperDroid Robots, U.S.A.	LT2-F "Bulldog"	7+ kg Full extension	40 kg	1220 mm	2 km/h	[7]
6.	SuperDroid Robots, U.S.A.	HD2-S "Mastiff"	9+ kg Full extension	68 kg Heaviest configuration	890 mm	2 km/h	[8]
7.	NIC Instruments Ltd., United Kingdom	ZEUS	15 kg	51.7 kg	1460 mm	3 km/h	[9]

tEODor EVO is an EOD robot developed by Telerob company. The robot is capable of performing not just EOD operations but also CBRN operations, which stands for Chemical, Biological, Radiological and Nuclear threats. It is equipped with a 6 degrees-of-freedom manipulator and an onboard tool magazine for convenient remote tool change. It has intuitive control handling and it is very popular with military and law enforcement agencies [3].

Andros F6A is an EOD robot developed by a subsidiary company of Northrop Grumman, Remotec Inc. It is distinguished by the capability to pneumatically release its wheels for width reduction when applications demand it. It is equipped with a 7 degrees-of-freedom manipulator and capable of 3-4 hours on mission operations [4].

TALON robots are EOD robots developed by QinetiQ Inc. They are in active service since 2000s when they were used in Bosnia and Herzegovina for the disposal of live explosives. TALON robots are also one of the lightest robots on the market that are equipped with multiple degrees-of-freedom manipulators. It can also be equipped with multiple cameras with the option to be mounted with thermal cameras as well. The advantage of TALON certainly is the number of options that the controller comes with, for example, it comes as LCU, meaning Laptop Control Unit, as well as TRC, Tactical Robot Controller [5].

T7 is a heavy-duty robot developed by L3Harris Technologies in the United States. It is designed to assist not exclusively EOD operations but also HAZMAT, meaning hazardous materials cleanup, intelligence and surveillance operations as well. It can be mounted with many different tools such as a disruptor, which blasts pressurized water to neutralize the threat on-site, a forklift and many different sensors such as the sensors for CBRN operations. One of the most significant characteristics of this robot is certainly the haptics control it utilizes. Haptics provide the operator with the sense of touch and proximity, almost as good as a bare hand can provide [6].

SuperDroid Robots company manufactures the model LT2-F, commonly known by the name "Bulldog". This model comes in many different configurations. It can be equipped with a 4-axis or a 6-axis arm manipulator, that can be equipped with wire cutters, different sensors for different applications. The arm manipulator can be shortened or removed as well to aid in low clearance areas. As previously listed models it can be applied in many different scenarios, ranging from EOD to remote surveillance and building cleanups [7].

HD2-S also known as the "Mastiff" is another model manufactured by SuperDroid Robots. This model is a bit bulkier model compared to LT2-F model. It as well comes in different configurations and can be equipped with wire cutters and application dependent sensors. Capable of staying operational up to 8 hours [8].

Zeus EOD robot is developed by NIC Instruments Ltd. It is a very reliable product that utilizes a very effective communication type, an FSK, meaning Frequency Shifting Keying, which is a communication type that employs alternating frequencies used in communication to avoid any noise disturbances. It is equipped with a battery capable of operating from 2-4 hours, mission dependent. It comes in different configuration with different arm sections, meaning different degrees-of-freedom manipulators [9].

The preferred communication in unmanned vehicles utilizes the EMS (Electromagnetic spectrum), between operator unit and robot, because it ensures a long range of operation. The waveforms of the communication are encrypted, especially when used in military applications [10]. Sometimes EMS is not applicable, because of strong interferences or large pieces of metal, which disrupt the signal. In those instances, some manufacturers provide a cable connection, which can reach up to 200 m, ideally a fiber optic cable [9].

The pricing of these robots is not readily available on the official websites of the companies. An interesting article, which presents cost-wise accessible EOD solutions, states that the range of prices for commercial robots, such as the ones presented in Table 1., is from \$40 000 to \$150 000 [11].

The purpose of this paper is to design a minimum viable product for EOD operations. An iterative design-build-test cycle is performed with the aim of developing a low-cost optimal physical platform for EOD robot in the category. The configuration test purpose is to quantitatively evaluate the packaging and setup tools used to start up the robot. The goal is to come up with metrics about the weight of packaging, setup time from configuration to deployment, weights of the control unit and the tools needed for repair. Particularly, the following objectives are achieved: physical design and development, mobility test on a flat paved terrain, mobility test with towing capacity, radio communications test by establishing a line of sight, manipulation test grasping dexterity and robot configuration for logistics tests.

2. Methods

The design of an EOD robot proposed by the authors was inspired by the robots readily available on the market. The base structure of the robot is made from steel bars, roughly 25 cm^2 in cross-section area. The bars are welded together to form a structure that consists of two rectangles connected by bars with an angle, as seen from the side. The rectangle closer to ground level is reinforced by bars welded to form a cross like symbol. Four DC motors are used to power mobility and they are welded on to the lower rectangle, with steel axels welded on them and to the wheels. The wheels are standard inflatable rubber wheels that come from small garden carts. The manipulator is made of three steel bar segments. The first segment is welded to the bottom of the base structure at its middle and extends some 50 cm from the weld. The second segment is welded to a door hinge which is welded to the first segment and the same procedure is applied to the third segment as well. The gripper is positioned at the end of the third segment and is made from aluminum. It is manufactured on a CNC machine and coated in plastics on the inside to secure maximum gripping. The manipulation of the arm is made possible by three linear electrical actuators which can lift weights up to 100 kg, respectively. The actuators are fastened to the segments of the arm manipulator by screws and nuts. The whole base structure is enclosed by plywood pieces and inside is the „brain" of the robot. Electronically, the robot is manipulated by simple relays which are powered through a car battery of 12 V. The opening and closing of switches, depending on the operation that needs to be applied, and the relays is controlled by Raspberry Pi which is powered by a power bank. The underlying circuit is called an H bridge. The communication with the robot is established through the wireless network connection that Raspberry Pi emits. The final design elaborated is presented in Figure 1. followed by Table 2. where the components used in the manufacturing are briefly presented.

As the title of this paper suggests, the authors presents a Minimum Viable Product (MVP), described as: "*a version of a new product that allows a team to collect the maximum amount of validated learning about the customers with the least amount of effort* ", by Eric Ries, founder of Lean Startup methodology [12].

Figure 1. Design of the robot

Table 2. List of components built in physical steel platform

Number.	Component	Specifications	Quantity
1.	Motor	12V high torque motors	4
2.	Wheel	20 cm diameter wheel	4
3.	Relay	5V 8 channel output relay board, maximum current 10A	2
4.	Raspberry Pi	Raspberry Pi model 4	1
5.	Battery	12V car battery	1
6.	Actuator	Linear electric actuator 12V, maximum load capacity 100 kg	3
7.	Power bank	5V DC power bank	1

It is important to emphasize the Viable part of the name as well as the Minimum part and not fall into the trap of favoring one over another [13]. In other words, the product has to satisfy the functionality requirements. The authors do emphasize that their design is not fully functional as compared to the robots listed in Table 1. in the introduction.

The Department of Homeland Security of U.S.A. alongside with the National Institute of Standards and Technology wrote a guide on the topic of testing and validating performance indicators of response robots, which include robots applied in dismantling explosive devices, searching for survivors in collapsed structures, investigating of illicit border tunnels and many more fields of application [14]. Under the sponsorship of Department of Homeland Security, the response robots undergo real-life scenarios which can include navigating through the test site and execution of different tasks such as: climbing stairs, handling of objects with manipulators, testing of communication range and many more [14]. The tests performed in this research are: Logistics - robot test configuration, Mobility on a flat paved terrain, Mobility with towing capacity, Radio communications - establishing a line of sight, Manipulation- grasping dexterity [14].

The mobility on a flat paved surface evaluates the speed of the robot. It is done by navigating the robot between two pylons 50 m apart. Average time is calculated from 10 repetitions. Mobility with towing capacity evaluates the maximum capacity the robot can tow on a flat paved surface. Average time for 10 repetitions is used as a metric. Radio communications test method establishes a line of sight which is the maximum downrange distance at which the robot completes the tasks to verify the functionality of control, video, audio and sensing mechanisms. Manipulation evaluates the grasping dexterity of the arm manipulator. It is measured by the number of pick-and-place operations a robot can complete in as little time possible.

In addition to tests elaborated above, energy consumption of the robot is also measured. It is evaluated using a multimeter, which measures how much current is drawn by actuators under specified load application.

3. Results and discussion

As a result of the methods used in the construction of the robot, the basic specifications of the robot are presented next. The robot`s base structure is roughly 590 mm in width, measurement which includes wheels, 820 mm in depth, measured from the center of the wheels and 340 mm in height, measured from the ground up. The arm manipulator has a maximum reach of roughly 1400 mm in horizontal direction and a maximum reach of 1200 mm in the vertical direction. The overall weight of the robot is roughly 55 kg, which includes all inside components. The dimensions are displayed in Figure 2.

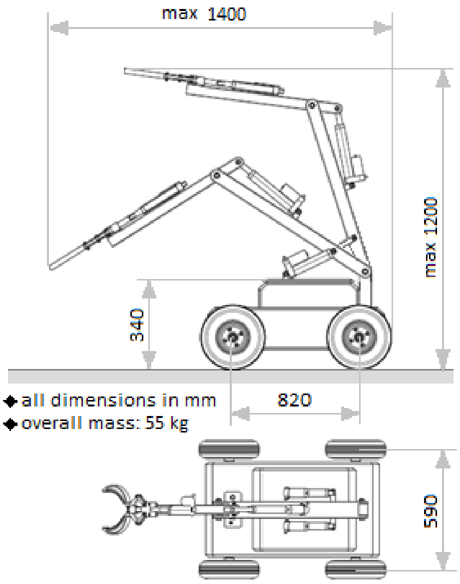

Figure 2. Dimensional sketch of the robot

The robot`s functionality is measured according to the guidelines presented in the methods section. The guideline was written by the Department of Homeland Security with its associates. The authors specifically chose applicable tests from the guideline such as setup time, speed test, mobility with towing capacity, radio communication test, object manipulation and lifting capacity. The test results are briefly presented in Table 3.

Table 3. Test results

Setup time	Speed	Mobility with towing capacity	Flat paved surface mobility	Radio communication test	Manipulation of objects	Lifting capacity
10 min	Up to 8km/h	40 kg	10 repetitions in 10 min	20 m line-of-sight	3 objects per 10 min	At full extension 15 kg

The first test conducted is the robot test configuration which measures the setup time of the robot and its equipment. The authors also took into consideration the transport of the robot using an automobile. Since the height of the arm, when all the actuators are in the fully retracted position, prevents the robot to fit into an average size automobile, a necessary measure is to dismantle the actuator, stemming from the base of the robot to the arm, to be able to fit the robot into the automobile. This increases the setup time which amounts to 10 minutes and includes: extracting the robot from the car, connecting the actuator that was dismantled previously, connecting the power wires to the car battery, connecting the power bank to the Raspberry Pi and finally connecting the laptop to the Wi-Fi connection of the Raspberry Pi. The most time-consuming setup process is surely the connection of the actuator which requires the use of ordinary plyers and a size 13 wrench. To conclude the results, setup time amounts to 10 minutes, with the weight of the equipment of 4 kg (laptop as the control unit, plyers and a wrench, additional wiring for repair).

The second test conducted is the „speed test“. According to authors measuring, the robot can achieve speeds up to 8 km/h, which is competitive enough. The authors note that the robot does not possess speed control, since the DC motors are taken form windshield car wipers and are programmed to utilize one speed of motion. On the bright side, these DC motors can generate around 30 Nm of torque, well enough to power the robot.

Mobility with towing capacity is the test that the authors conducted inside the laboratory where the robot is constructed. The maximum tow value tested is 40 kg. The robot`s capability of towing motion was also successfully tested with the towing of a wheeled chair with a person sitting on the chair. Although the chair is wheeled, this test proves that the robot has substantial towing capacity.

Radio communications test, testes the capability of the robot to continue working and receiving signals from the control unit far away from it. This test is probably the weakest point of the robot, since the communication with the robot is achieved through Wi-Fi signal of the Raspberry Pi. The furthest distance away from the control unit, at which the communication still operates without interferences is roughly around 20 m. This distance is further lowered with the introduction of obstacles such as walls. This weak point is surely something the authors are working to improve.

Manipulation of objects is a test which measures the capability of the robot to pick-and-place as many objects in as little time possible. The authors do mention here that the gripper is designed in a such a way, that the objects need to be gripped with the very tip of the gripper in order to lift them. This especially applies to thin objects such as bottles, which would otherwise fall through the gripper because of the width of the gripper at its middle. The authors manipulated objects such as bottles, desk chairs, bricks, metal objects etc. One of the disadvantages of the gripping of the robot is the fact that the whole robot needs to be moved in order to place the end of the gripper in the position to grab an object. This is due to the fact that the arm can only be manipulated in the vertical direction. To conclude, due to the limitations in the mobility of the arm, the robot can pick-and-place only 3 objects in the time span of 10 minutes.

In addition to these tests, a diagram of the lifting capacity of the robot is presented in Figure 3. below. The outer circle presents the lifting capacity at maximum extension and the inner circle represents the lifting capacity at full retraction. These values can be narrowed down to a single value because the lifting is executed only using one actuator at a time. Here the values differ only because of the fact that the arm is loosely constructed and is not capable of handling higher loads at full extension.

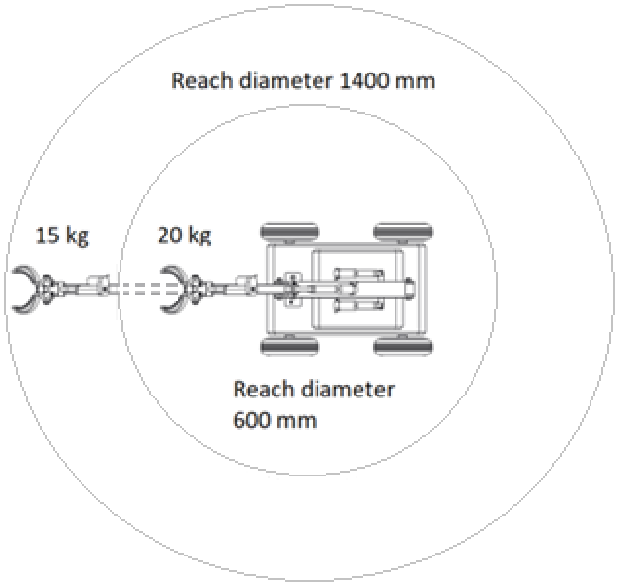

Figure 3. Lifting capacity in relation to reach

Further tests are related to energy consumption also related to the lifting capacity. The relationship between current consumption and lifting capacity is shown in Figure 4.

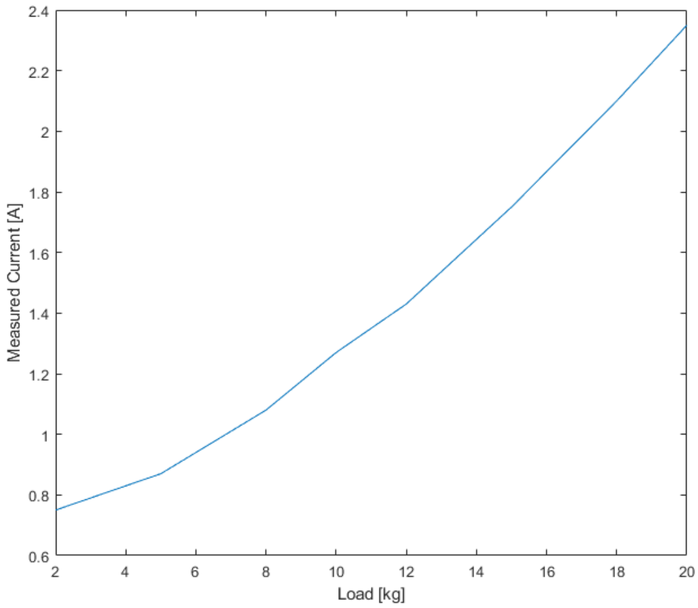

Figure 4. Current consumption vs. load values

Figure 4. shows current consumption on different loads expressed in kg that is needed for actuator. It can be seen that the relationship is almost linear. Also considering manufacturer's datasheets it should be indeed linear. Peak current consumption is 2.3 - 2.5 A for the 20 kg load with 12 V source configuration. For loads less than 6 kg energy consumption is 1 A or less. Power-vise 30 W of power is used at peak. Measurement is done by using a multimeter device (also can be done using amperemeter or oscilloscope). Actuators are connected in series and tested for various loads with constant 12 V voltage supply. Figure 5. below shows how speed of the motor is slowly decreasing when the load is increased. The relationship is also linear.

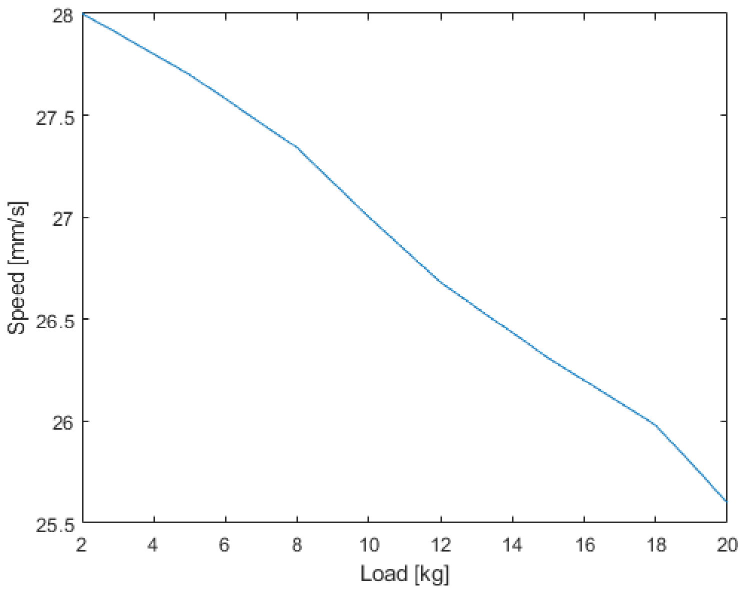

Figure 5. Speed vs. load values

Value drops slightly from 28 mm/s for load <2 kg to around 25.6 mm/s for the 20 kg load. First measurement experiment is done using timer and measuring tape. Time is measured for 5 seconds with exact starting point after which distance is measured after timer is stopped. This measurement was repeated several times. Second technique was directly programming actuators to be switched for exact amount of time controlled by main controller. This gives exact and more precise time of 5 s.

Based on the test result obtained in this research, a comparative analysis is done and the results are listed in Table 4.

Table 4 in this research briefly presents the comparative advantages and disadvantages of authors EOD robot to the robots availaible from Table 1. in the introduction section. In a nutshell, authors robot is lower in performance features compared to models tEODor EVO and model T7, which mainly reflects in lower weight and lifting capabilities. On the other hand, lower cost presents an important advantage compared to these two models.

Competitive performances can also be observed compared to models ZEUS, HD2-S, LT2-F, Andros F6A. These are mainly in regards to reach and lifting capacity. A significant advantage in lifting capacity, speed and reach potential performances are achieved compared to models HD2-S, LT2-F and Andros F6A. To summarize, authors EOD robot has a high potential to compete against the models already available on the market.

Table 4. Comparative results

Model	Specification	This EOD robot
This EOD Robot	Max. lift capacity: 20 kg Weight: 55 kg Reach (Forward): 1400 mm Speed: Up to 8 km/h	• Competitive in category
tEODor EVO [3]	Max. lift capacity: 100 kg Weight: 383 kg Reach (Forward): 1860 mm Speed: 3 km/h	• Lower category • Lower performances • Lower cost as an advantage
Andros F6A [4]	Max. lift capacity: 61 kg Weight: 220 kg Reach (Forward): 1440 mm Speed: 4.8 km/h	• Same category • Competitive reach potential • Higher speed of mobility • Lower overall weight
TALON [5]	Max. lift capacity: 68 kg Weight: 81 kg Reach (Forward): 1570 mm Speed:	• Same category • Lower lifting capacity
T7 [6]	Max. lift capacity: 113+ kg Weight: 322 kg Reach (Forward): 2200 mm Speed: 8+ km/h	• Lower category • Significantly lower lifting capacity • Lower reach
LT2-F “Bulldog” [7]	Max. lift capacity: 7+ kg Full extension Weight: 40 kg Reach (Forward): 1220 mm Speed: 2 km/h	• Same category • Significantly higher lift capacity • Competitive performances per each parameter • Lower cost as an advantage
HD2-S “Mastiff” [8]	Max. lift capacity: 9+ kg Full extension Weight: 68 kg, with the heaviest configuration Reach (Forward): 890 mm Speed: 2 km/h	• Significantly higher reach potential • Higher speed of mobility • Competitive overall weight • Higher lifting capacity at full extension
ZEUS [9]	Max. lift capacity: 15 kg Weight: 51.7 kg Reach (Forward): 1460 mm Speed: 3 km/h	• Same category • Higher overall weight • Competitive reach potential • Competitive lift capacity

4. Conclusion

This paper presents the design and development of an MVP EOD robot, specifically designed to operate with explosive devices in their removal, disposal and neutralization. This MVP design is functionality-wise limited, due to budget limitations, but nevertheless, presents a solid opportunity for testing and presentation purposes. The final design is 590x820x340 mm in dimensions, weighs 55 kg with a maximum manipulator reach of 1400 mm. The vertical reach is 1200 mm.

The setup time of the robot with all of its configurations is 10 minutes, and the equipment weighs 4 kg which includes a laptop, as a control unit, plyers, a wrench and some additional wiring for repairs. Compared to models from Table 1. authors robot lacks a control unit which is highly durable and easily carried. Other equipment is carried independently and also lacks a custom-made bag. The setup time is mostly slowed because of the fact that the manipulator must be partially dismantled to fit into an average size car. Models from Table 1. Usually come with a modular manipulator and other accessories which are easily mounted on the robot. Slower setup time is also due to the fact that the Raspberry Pi needs to be manually turned on with a power cable and the program needs to be compiled each time the session is ended. Fortunately, these specifications are easily made easier and improved. The robot can reach a speed of 8 km/h due to its high torque DC motors. The towing capacity is roughly 40 kg, which highly depends on the surface of the motion.

The weakest point in the design is the communication reach, which is limited by Wi-Fi signal, to 20 m. The second weakest point is the gripping, which needs to be very precise, especially for thin, narrow objects, such as bottles. Compared to the robots from Table 1, this low-cost EOD robot platform represents a solid foundation into further design and development endeavors, which will hopefully take place in the near future. The plan for future work is to upgrade the existing physical platform to an autonomous EOD robot with the ability to detect explosive devices and mark them or safely dispose of them.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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