# Design and Development of Explosion-proof Tracked Vehicle for Inspection of Offshore Oil Plant

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**Abstract** French oil company TOTAL and ANR (L'Agence Nationale de la Recherche) organize the ARGOS (Autonomous Robot for Gas and Oil Sites) Challenge, which our research group had the opportunity to participate in. ARGOS is a research and development competition for mobile robots capable of autonomous inspection of instruments and teleoperated information gathering in oil plants, in place of human workers. One of the features of this challenge is that robots should be constructed with explosion-proof structures, because the target plants may have explosive atmospheres. To participate in the third competition of the ARGOS Challenge in March 2017, we developed AIR-K, an explosion-proof robot. The AIR-K is divided into three parts to make it explosion-proof. According to the features for robot functions and sensors, it uses a flameproof battery enclosure (Ex 'd'), a pressurized apparatus (Ex 'p') for its body, and intrinsic safety (Ex 'i') for sensors; the explosion-proof of the robot is achieved by a combination of these methods. In this paper, we introduce the design guidelines and implementations that allow our robot to be explosion-proof.

## 1 Introduction

In recent years in Japan, the practical use of field robots is expected for economic improvement, reduction of dangerous tasks, and social creation. Therefore, industries, government, and academia are continually researching and developing such robots. In particular, the aging of social infrastructure and plants constructed during periods of high economic growth is a significant problem. Therefore, the introduc-

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**Fig. 1** AIR-K prototype (non-explosion-proof version) in ARGOS Challenge.

tion of robot-based maintenance management methods is recommended to solve the problem. With such robotic technologies, it is expected that the lifetime of the infrastructure will be extended and the total cost of maintenance will be reduced [1].

The need for robotic inspection of infrastructure and plants is not limited to Japan — it is a common problem for nations that possess similar facilities. A concrete example is the oil spill that occurred at the Deepwater Horizon in the Gulf of Mexico on April 20, 2010. During the accident, the concerned facility should have been investigated. However, it was impossible to enter the plant because it was too dangerous for human inspectors.

To facilitate robotic investigations in emergency situations, and inspections during normal operations, French oil company TOTAL and ANR (L'Agence Nationale de la Recherche) organized the ARGOS (Autonomous Robot for Gas and Oil Sites) Challenge, which was launched in December 2013. ARGOS was a research and development competition for mobile robots capable of autonomous inspection of instruments and teleoperated information collection in oil plants, in place of human workers. Five international teams, including ours, were selected for the challenge, based on a document review. One of the features of this challenge was that robots should be constructed with explosion-proof structures, because the target plants may have explosive atmospheres. Figure 1 shows a scene from the ARGOS Challenge final competition in March 2017.

Few small mobile robots have obtained explosion-proof certificates. It can be said that Sakura-II was the first small mobile robot with explosion-proof certification. It was developed by Mitsubishi Heavy Industries Ltd. with a New Energy and Industrial Technology Development Organization (NEDO) research grant for surveillance of tunnel disasters. The robot was certified according to the explosion protection (zone-1) of the Japanese standard (IEC spec conformable), which is almost equivalent to ATEX Cat.2.

With reference to the above robot, we conducted research and development of an explosion-proof robot, called AIR-K, in order to participate in the third competition of the ARGOS Challenge in March 2017. In this paper, we introduce the design guidelines and implementation for our explosion-proof robot.

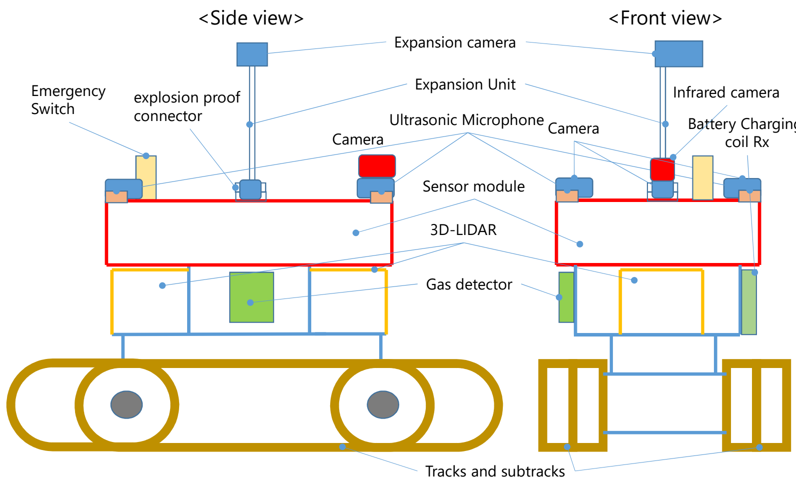


**Fig. 2** Configuration of sensors and actuators on the AIR-K.

## 2 Design guidelines of AIR-K

### *2.1 Requirements*

The objectives of AIR-K are autonomous inspection of instruments during normal operations and teleoperated observations in emergency situations (e.g., gas leaks and fires). Therefore, the AIR-K requires numerous capabilities, including image processing, sound detection, temperature detection, gas detection, obstacle detection, localization, and stair traversal. To provide such capabilities, the following sensors and mechanisms were installed onto the AIR-K.

- Image processing: Six optic cameras were installed.
- Sound detection: Four ultrasound microphones were installed.
- Temperature detection: A thermal camera was installed.
- Gas detection: A gas sensor was installed.
- Localization, obstacle detection: Two 3D LIDARs were installed in the front and back.
- Stair traversal: Four subtracks were installed to negotiate stairs.

The configuration of the sensors on the robot is shown in Figure2.

### *2.2 Design guidelines providing explosion-proof structure*

To make the AIR-K explosion-proof, we performed design and development based on the following requirements:

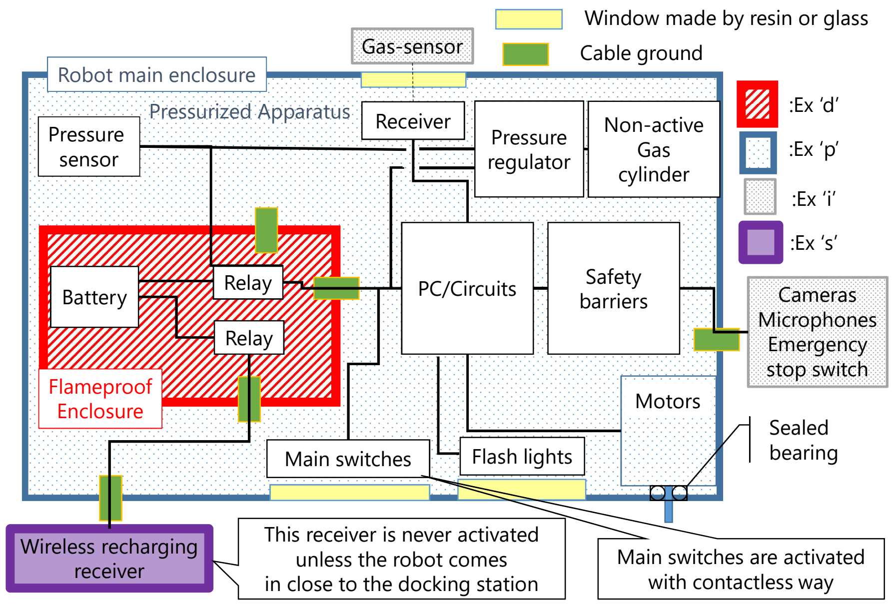


**Fig. 3** Block diagram of components of AIR-K.

1. Hazardous region: zone 1
2. Gas group: IIA
3. Temperature class: T3

where the explanation of the standards are in [2]. The hazardous region is zone 1, so the equipment protection level (EPL) should be Ga or Gb.

The AIR-K is divided into three parts to make it explosion-proof. Figure 3 shows a block diagram of the components of AIR-K. According to the features of robot functions/sensors, it uses a flameproof enclosure (Ex 'd'), a pressurized apparatus (Ex 'p'), and intrinsic safety (EX 'i'); its explosion-proof capability is achieved by a combination of these methods.

The basic idea of the whole explosion proof of AIR-K is as follows:

1. A type 'd' flameproof enclosure protects the battery based on the philosophy of "ensuring its explosion proof capability even when the battery discharges all energy." It is located inside the pressurized apparatus. The battery has the potential to ignite. However, when a flameproof enclosure covers it, and when the enclosure is located inside of the pressurized apparatus, it can meet the following requirement: "a device with ignitability is not built in the internal pressure container in the normal state."
2. Some electric sensors, such as microphones and cameras, are difficult to make pressurized apparatus, individually. One possible method is that the internal pressure of the sensor is kept equal to the inside of the main body by using the through-holes. However, restrictions on design are large, and expandability is

also impaired. Therefore, we configured intrinsically safe devices and located outside of the robot. The protection type is Ex 'i'.

3. Other equipment, such as PC and integrated flashlight located inside the pressurized apparatus, do not have a flameproof enclosure. So, these are assumed to be ignition capable apparatus (ICA). Therefore, the protection type is Ex 'p'.

We introduce additional design and implementation details for the flameproof battery enclosure in section 3, the pressurized apparatus for the robot body in section 4, and the intrinsically safe sensors in section 5; other requirements for explosion-proof capability are discussed in section 6.

## 3 Flameproof Enclosure for batteries

A type 'd' flameproof enclosure protects the battery module. The whole module, including the flameproof container with the battery inside, is placed inside the pressurized apparatus (IEC60079-1 [3]). Thus, the module secures a protected circuit in cases where the internal pressure cannot be sustained. In addition, this circuit is connected to a pressure sensor that measures the pressure balance between the inside and outside of the explosion-proof structure. If the internal pressure is not at least +50 Pa higher than the external pressure, the relay inside the flameproof container will be switched off, so that the battery's energy will not be discharged to the outside of the container. The protection type is 'px,' so this mechanism must be dual redundant. Because the battery must be rechargeable, the AIR-K's battery is charged by a contactless electricity transmission coil. This configuration was chosen because it is assumed that the robot will be deployed on offshore platforms, where it may experience salty breezes and rain. If the battery is charged via a connected charger, there is a possibility of power leakage from a short circuit. Thus, we strongly believe that a contactless charging system is essential, even if the charging system is placed in the non-explosive atmosphere.

The coil for receiving the power from the contactless charging system is placed on the outer side of the robot (Figure 3), which is connected to the charging circuit located inside the pressurized apparatus. The charging circuit is connected to the battery inside the flameproof container via the double protection circuit including the relay (Figure 4). The coil protection circuit actuates only when power is supplied from the charging station located in the non-explosive atmosphere, which makes it a non-electric component in hazardous zones. However, all cables that connect the inside and outside of the flameproof container satisfy IEC60079-1 section 13 [3].

Standards for explosion-proof batteries state that cells must be connected in series only. Thus, lithium-ion batteries (L1A0N8C1: Maxell [4]) should be connected in series. However, owing to Japanese aviation regulations, we cannot transport such battery via an airplane. Therefore, as an alternative for the AIR-K, we chose a battery (DUO-150: IDX) that could be transported to the ARGOS challenge. Figure 4 shows a battery module diagram for the AIR-K.

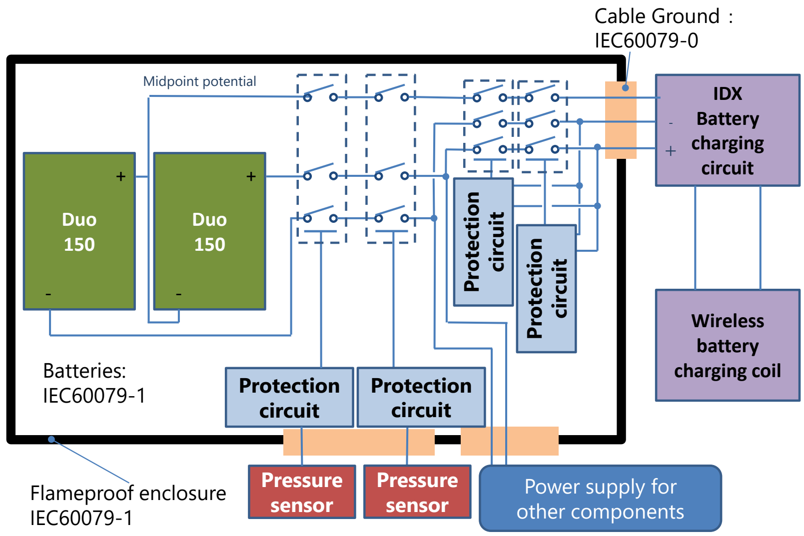


**Fig. 4** Battery module diagram for AIR-K.

We conducted initial functional tests in which the robot was switched off when the internal pressure became lower than the external pressure, and confirmed that the functionality worked as we expected.

## 4 Pressurized apparatus for robot body

The Ex ’p’ pressurization method protects the robot body. The inner pressure should be 50 Pa higher than the outside pressure (IEC60079-2, section 7.10 “Value of overpressure” [5]). Therefore, the AIR-K is equipped with an intake gas cylinder that contains an inert gas, and the inner pressure is adjusted by controlling a solenoid valve attached to the cylinder to supply the gas. Figure 5 shows a block diagram of the AIR-K’s internal pressure regulator. It uses a differential pressure sensor to control the inner pressure, and the threshold for opening/closing the valve is 1 kPa. Once the robot opens the valve, the inert gas is supplied to the robot body. The threshold value can be changed, and it is a temporary value, at present.

Figure 6 shows the relationship between the differential pressure sensor and the status of the solenoid valve. When the inner pressure decreases, the robot opens the valve, and then the inner pressure increases. On the other hand, if an abnormal pressure drop occurs (the differential pressure sensor detects that the difference between the inner pressure and outside pressure is lower than 200 Pa), the system shuts down the battery module. Thus, the output voltage of the battery is never exposed to the outside of the flameproof enclosure.

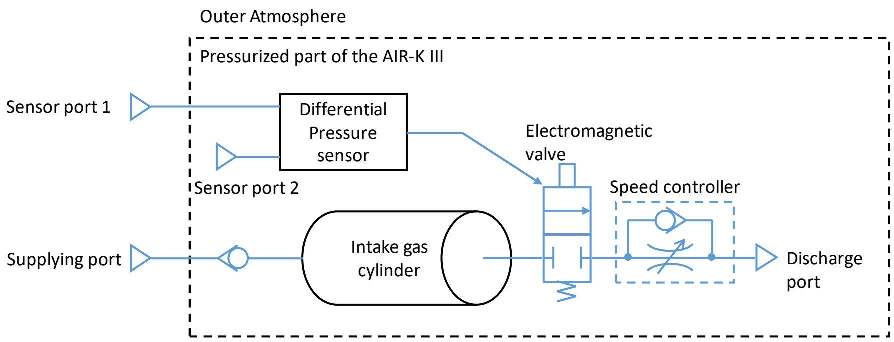


**Fig. 5** Diagram of pressurized apparatus for AIR-K

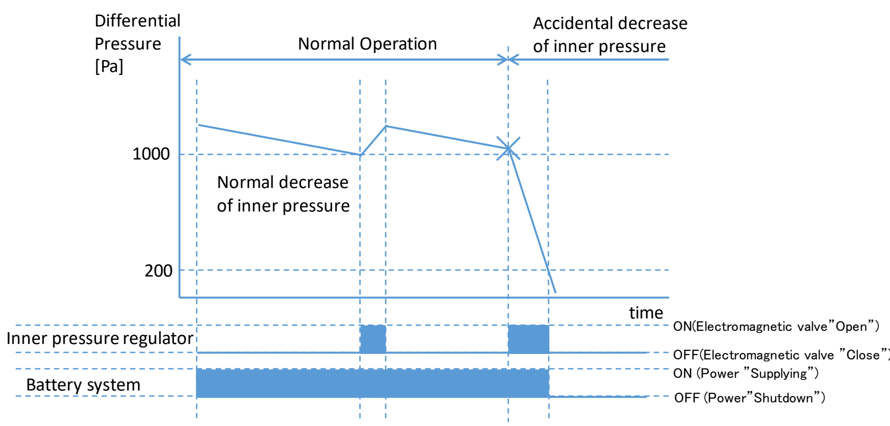


**Fig. 6** Relationship between pressure sensor and solenoid valve.

As described above, the inside of the AIR-K is equipped with an intake gas cylinder to supply inert gas. Therefore, AIR-K is assumed to use a pressurized apparatus structure with a leakage compensation method. Figure 7-left shows a CAD model of the bottom part of the robot, and Figure 7-right shows the actual location of the gas supply valve. According to Technology Institution of Industrial Safety (TISS) in Japan, scavenging air is not required based on this method. Therefore, AIR-K does not have a function to scavenge air.

In the implementation of AIR-K ' s pressurized apparatus, the following values are ensured:

- Maximum: Outside pressure + 2 kPa
- Minimum: Outside pressure + 50 Pa
- Operating: Outside pressure +1kPa (Reference value)

The minimum pressure value of "outside pressure + 50Pa" is the same as the value of type px in IEC60079-2, section 7.10, "Value of overpressure" [5].

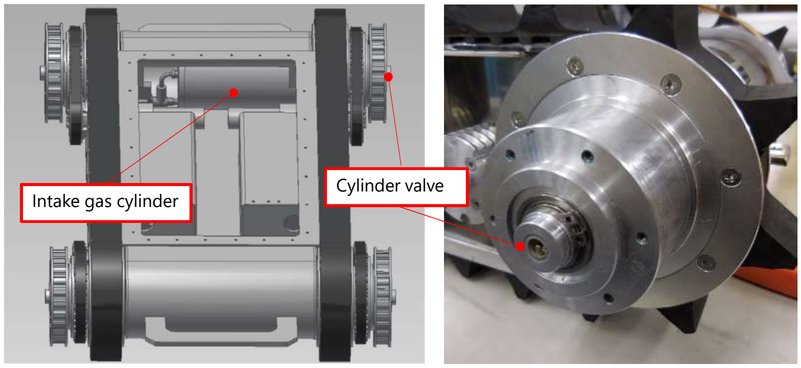


**Fig. 7** Intake gas cylinder and cylinder valve.

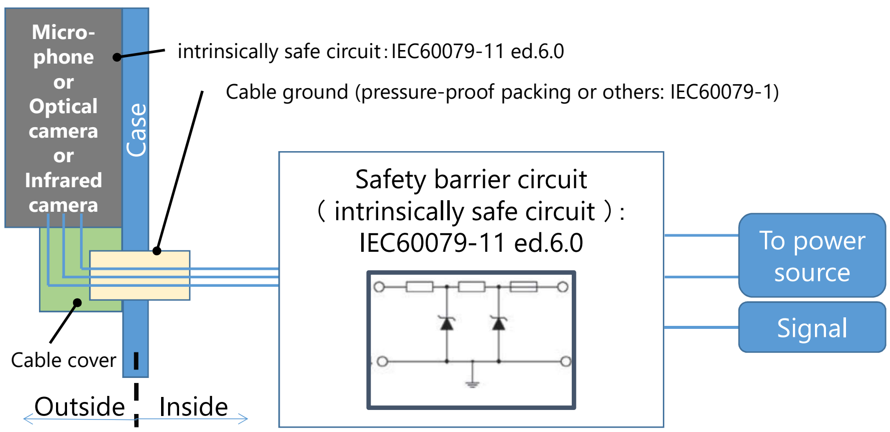


**Fig. 8** Diagram of intrinsically safe configuration for cameras, etc.

To confirm the safety of the pressurized apparatus, the strength of the robot's body must be tested. The test includes a 1 kg-sharp-weight-drop from a height of more than 70 cm (IEC60079-26.4.2).

## 5 Intrinsically safe configuration for sensors

The microphones, optical cameras, infrared camera, and gas sensor are difficult to make pressurized apparatus, individually, as described in Section 2.2. Therefore, these are configured as intrinsically safe devices.

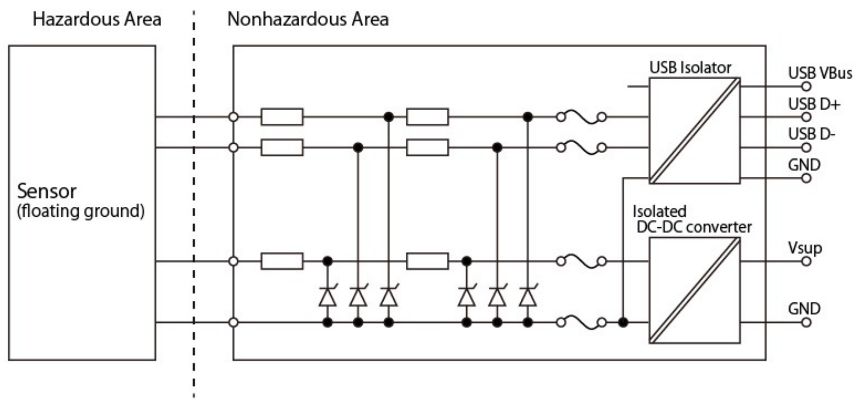


**Fig. 9** Isolated barrier circuit for USB devices.

## *5.1 Intrinsically safe configuration for optical and thermal cameras*

Six optical cameras and one thermal camera are mounted on the robot to measure the instruments, to detect heat sources, and to send images for teleoperation. These sensors have an intrinsic safety structure and are designed according to IEC60079-11 [6]. We install these modules outside the robot's body, and connect the signal and power lines to the controller located inside the pressurized apparatus via protected circuits. Therefore, they will not become an ignition source even when a short circuit occurs.

There are mainly two types of protected circuits: Zener barrier and isolated barrier. A Zener barrier requires an A-class earthing, so it is not applicable for mobile robots. Therefore, the robot adopts the isolated barrier so that there is no need for earthing. We configure the barrier circuit with the following components:

- Isolator: Insulates the USB communication line and power to prevent unintended ground loops.
- Current/Voltage regulation circuit: Prevents ignition even when there is a circuit failure or short circuit. Resistance and Zener diodes are used.

USB isolators (USB-029L2, HuMANDATA co., Ltd.) and DC-DC converters were selected, with a dielectric strength voltage of 2000 V. The factor of safety was 3.5, calculated from the French power source's peak voltage of 564 V. Figure 9 shows an isolated barrier circuit for USB devices.

The current limiting resistor in the barrier circuit is designed to satisfy the condition described in CENELEC (European Committee for Electrotechnical Standardization). Particularly, since the power lines send electricity, if the 5V from the USB is supplied directly to the line, it will not satisfy the requirements. So, a voltage

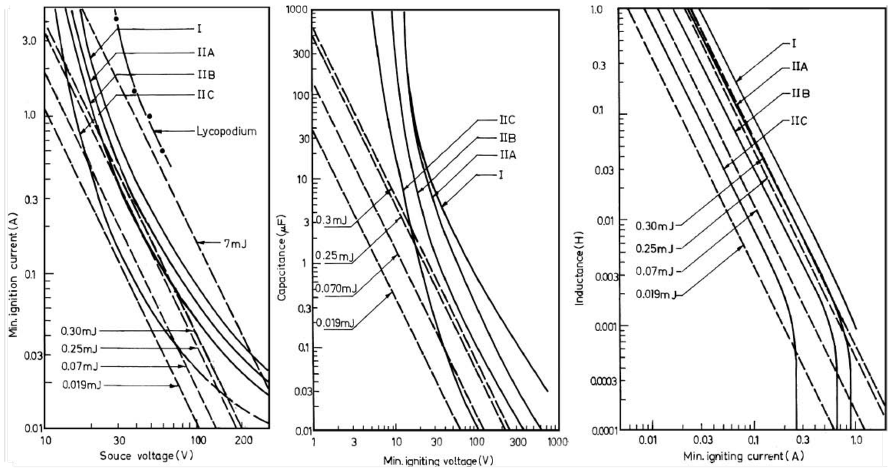


**Fig. 10** Standards to determine if the system will ignite or not. [7]

larger than 5V is used to produce 5V at the device, the electricity should be at a lower current. The value of the current limiting resistor was calculated by model-based design method.

$I_{short}$, the maximum current to avoid explosion when there is a short circuit, is calculated as

$$I_{short} = \frac{E}{R}, \tag{1}$$

where power voltage denotes $E$, and current limiting resistor $R$.

On the other hand, $I$, the current at maximum load for functioning devices, is calcuated as

$$I = \frac{E - \sqrt{E^2 - 4 \cdot R \cdot P/eff}}{2 \cdot R}, \tag{2}$$

where electricity conversion efficiency (at the device) $eff$ and the maximum power consumption (at the device) $P$. It is the equation to obtain the necessary current for the DC-DC converter to drive the devices under certain protection resistance and voltage. In case the resistance is too large, the power cannot be supplied, and $I$ becomes an imaginary number. Therefore, $I$ should be a real number to supply the power.

To avoid ignition when there is a short circuit, the circuit has to be under the Current-Inductance curve, Voltage-Electrostatic capacity curve, Current-Voltage curve, as shown in Figure 10. The worst case scenario for ignition from induced currents is when a line is a cutoff, and the short circuit triggers another cutoff. So, $I_{short}$ and inductance of circuit $L$ must be below the Current-Inductance curve. The worst case scenario for ignition from the circuit capacity is when a line is a cutoff, the circuit is open, and the electrostatic capacity reaches the power voltage before triggering a cutoff. So, $E$ and capacity of circuit $C$ must be below the Voltage-Electrostatic capacity curve. The worst case scenario for ignition from the current/voltage of the barrier circuit has many conditions, so the design is made on the conservative side. Taking into account the worst case scenario for the current/voltage, $E$, $I_{short}$ must be below Current-Voltage curve.

Based on a full search in 2-dimensional parameter space of current limiting resistor and supply voltage, these parameters are set as 66 Ω and 23.8 V. Using these parameters, the factor of safety of 5 for the ignition energy can be guaranteed.

By setting the USB signal level to 3.3V, and inserting a 36 Ω current limiting resistor, the signal lines is guaranteed with a factor of the safety of 10. It is more conservative parameter.

### 5.2 Intrinsically safe configuration for ultrasonic sensors

Four ultrasonic microphone modules were mounted to detect gas leak sounds and to locate the source. This module has an intrinsic safety explosion-proof structure that is similar to those of the optical and thermal cameras, as per the standard stated in IEC60079-11 [6]. We installed these modules outside the robot's body, and connected the signal and power lines to the controller located inside the pressurized apparatus via protected circuits; this prevents them from becoming an ignition source, even when a short circuit occurs.

The microphone module consumes very little power; thus, it does not have a power line, and operates using the weak current from the signal line. Each signal line is connected to the microphone module in the isolated barrier circuit via a current/voltage limited circuit and an isolated circuit. The current/voltage limited circuit is identical to that of the USB signal lines of the optical and thermal camera modules, with a factor of safety of greater than 10 (even when a short circuit occurs).

### 5.3 Gas sensors

A GX-2009 (RIKEN KEIKI Co., Ltd.) gas detector is mounted on the robot for detecting flammable gas. The structure of this sensor is intrinsically safe Ex 'i' (Exia CT4X), with a certificate from TIIS. It is also IP67-equivalent waterproof. This sensor performs infrared communication (IrDA) via a Pro Plus (ABS510700), a special LEGASTIC IrCOMM adaptor receiver, to communicate with external interfaces. To enable the robot to detect flammable gas, we locate the detector outside of the pressurized apparatus, and locate the receiver inside the apparatus. The infrared source and receiver face each other, which enables communication through the transparent body.

We connect a power cable from the battery module to the sensor to extend the activity of the sensor. To guarantee its intrinsic safety, the maximum voltage is set to 5 V, and the current limiting resistor is set to 36 Ω to ensure that the current is within 30-50 mA (factor of safety: greater than 70).

## 6 Other requirements for explosion-proof operation

### *6.1 Dissipation of static electricity buildup*

The non-metal materials (plastic) used for the robot enclosure must satisfy at least one of the conditions below.

1. Surface resistivity based on the measurement method specified in IEC60079-0 section 26.13 is below $10^9$ Ω/sq.
2. Maximum surface area is below 10,000 $mm^2$ (Equivalent to EPL 'Gb')
3. Maximum layer thickness is below 2 mm (Equivalent to EPL 'Gb')

These conditions are intended to prevent static electricity, and are stated in IEC60079-0, section 7.4. (If the material is categorized as Gas Group II A, and Equipment Protection Level (EPL) 'Gb.')

On the other hand, plastic materials are used for the following sections inside the AIR-K robot: (1) Charging coil case, (2) Light transmitting plate, (3) 3D LIDAR case (includes translucent parts), (4) Wireless LAN enclosure, (5) Base plate for Gas sensor, (6) Base plate for receiver of Gas sensor, (7) Ultrasonic microphone case, (8) Thermal camera case, (9) Optical camera case, and (10) Main switch case. The surface areas of objects (2)-(10) are each below 10,000 $mm^2$. In the case of (1), the surface area of its acrylic case exceeds 10,000 $mm^2$, and the surface resistivity is 1,016 $\Omega$. Therefore, we should spray an anti-electrostatic agent on the surface to satisfy the standards.

### *6.2 Earthing arrangement*

The earthing arrangement is stated in IEC60079-0 (Connection facilities for earthing or bonding conductors), and equipment that needs grounding is described in section 15.1. On the other hand, equipment that does not require grounding is described in section 15.2, and the following statement is provided: "for which supplementary earthing is not necessary, an internal or external earthing or bonding facility need not be provided."

According to the following reasons, AIR-K can be classified as "Safety Extra Low Voltage" (SELV), and it does not require grounding.

1. There is no connection to the primary power supply in the danger zone.
2. The potential difference of the robot is a maximum of 34 V, and it does not exceed 42.4 V (which corresponds to a dangerous level of current for humans).

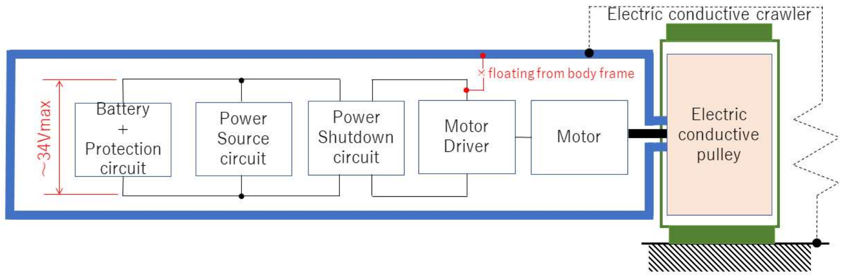


**Fig. 11** Earthing structure of AIR-K.


**Fig. 12** Explosion-proof robot AIR-K Ver.3.

3. The surface of the robot has the same electric potential, and the potential difference between two arbitrary points (one point may be broken) is safe for human contact.

Figure 11 shows the earthing structure of AIR-K.

As described above, AIR-K does not require grounding. However, conductive belts should be used for tracks to satisfy high electrostatic breakdown strength, as described in IEC60079-0, section 7.4 (Electrostatic charges on external non-metallic materials). Therefore, for safety considerations, the structure has simply secured grounding.

## 7 Conclusions

In this study, we conducted research and development to create a mobile robot (AIR-K) as our participation entry for the ARGOS Challenge 3rd competition. The robot's explosion-proof design was based on the IEC60079 series standard. As shown in this paper, the robot uses a flameproof enclosure (Ex 'd'), a pressurized apparatus (Ex 'p'), and intrinsic safety (EX 'i'), and its explosion-proof is achieved by a combination of these methods. Figure 12 shows an image of the developed robot. Because of a problem with the locomotion, we did not use the robot in the 3rd competition but attended with a non-explosion-proof AIR-K prototype.

Because of space limitations, not all tests to confirm the robot's explosion-proof capabilities were described in this paper. However, to obtain an explosion-proof certificate for the robot, remaining issues must be solved and additional tests must be cleared. As the main issues, the robot must consist of cells connected in series only, according to explosion-proof standards for batteries. We need to replace the serial battery configuration and conduct tests on their flameproof capabilities. Second, a thermal test inside the robot should be conducted during operations. Third, a strength test of the body should be conducted to confirm the safety of the pressurized apparatus.

In the future, we plan to develop explosion-proof mobile robots for autonomous inspection in oil plants, based on our experience from the above research and development.

**Acknowledgements** The ARGOS Challenge [8] supported this work.

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