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An humanoid robot for inspections and cleaning tasks in nuclear glove box

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Abstract— This article presents an opportunity evaluation of the use of humanoid robots in a nuclear environment. The project worked on the DaRwIn-OP platform to assess and carry out the modifications the robot needed to enable it to perform as an intervention operator in a nuclear location. The study had two main lines, based on equipping the humanoid with a radiological measurement capture system and with an arm command system using a depth camera. The tests performed showed the robot's ability to make radiological measurements with the built in detector and to collect swipe samples to assess the contamination of an object.

I. INTRODUCTION

This article describes the results of work intended to prepare a humanoid robot for work in a nuclear environment where the irradiation and contamination mean human intervention must be severely limited. The use of anthropomorphic robotics arises from the theory that a biped humanoid with gripping hands has the ability to replace humans for work in an extreme or hostile environment. Such a robot's means of movement should offer the advantage of being well-adapted to surfaces inaccessible by more classic robot locomotion systems based on wheels or tracks [1]. Its human-like ability to grip and handle objects with its hands appears to represent a real opportunity, as does the control of this sort of robot by having it imitate the movements of an operator located outside the hazardous zone [2]. Given these factors, work was undertaken on a humanoid platform in order to evaluate the opportunity of making it into a robotized assistance operator for nuclear environment investigations. This project followed up on analyses of the possibilities offered by a link between the D&D industry and the open-source robotic community [3]. The humanoid robot was called H@RI, a French acronym for Robotized Assistance Humanoid for Investigation. This article first describes the pre-existing technological bricks used in the trials, i.e. the DaRwIn-Op [4] humanoid robot and the radiological detector used (II). Next, the work carried out on the platform software part, the integration of a nuclearized instrumentation and the robot control are explained (Section III). Finally, different tests are presented concerning the irradiation of the on-board electronics, the on-board radiological detector validation and

the remotely-handled control capacity for taking a swipe sample (Section IV).

II. THE EXISTING EQUIPMENT

A robot can be considered as a match between hardware and middleware systems, on which a set of tools and detectors has been installed. This view is the basis of the following presentation of the platform used, and of the tools added on. In this section, the humanoid robot platform (Section II-A) the software system structuring all the developments carried out (Section II-B) and then the radiological detector which was built onto the humanoid (Section II-C) are described. The H@RI robot's tools made it a suitable intervention operator for hostile environments, able to take measurements which provide further useful data in the radiological characterization of a nuclear environment.

A. Hardware

On order to avoid the cost of designing a completely new humanoid robot, it was decided to use an existing platform. The well-known DARwIn-OP (Dynamic Anthropomorphic Robot with Intelligence – Open Platform) marketed by ROBOTIS [5] was chosen. This robot is 45.5 cm tall and weighs 2.8 kg. Its size and weight features mean that each of the joints is controlled by a single servomotor. The MX-28 servomotors were developed specifically for this robot in order to have the best possible resolution and communication speed compared to RX-28 type servomotors, in particular by using PID type control methods [6]. The DARwIn-OP robot is available off the shelf with an Intel Atom Z530 @ 1.6 GHz main controller with 1 GB RAM and 4 GB of memory. Communication is via HDMI, USB, flash memory, Ethernet or even Wi-fi type external ports. The robot is powered by lithium batteries.

B. Firmware

The platform is delivered with a Linux Ubuntu 9.10 operating system. The open-DARwIn-SDK framework, in C++ programming language, was specifically created for this platform. The development team wished to make it a modular architecture [7] grouping all the necessary functions : communication, walking, vision, etc. The framework was modified to avoid the developments carried out during this project being not just for this particular robot, as will be discussed in Section III-A.

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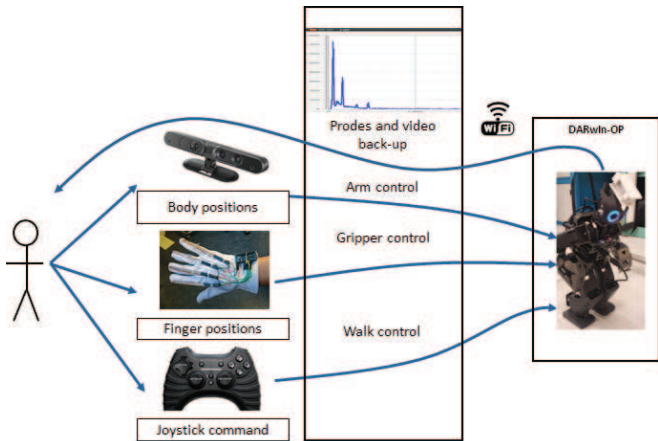
Fig. 1: Functional architecture

Fig. 2: GR1 detector attached to H@RI's head

C. Tools

H@RI had to be able to contribute to characterizing the radiological state of its operation zones. Among the different possible analysis techniques, it was decided to retain gamma spectrometry, as it enables the identification and quantification of gamma emitting radionuclides. H@RI was equipped with a gamma spectrometry detector whose hardware and software had to be built in. The small size of the humanoid platform meant a small-scale, lightweight gamma spectrometry line had to be used. These precautions are important to enable easy integration onto the robot's structure without disturbing its dynamic model. The GR1 detector, marketed by KROMEK, with dimensions of 62 $\times$ 25 $\times$ 25 mm and weighing 60 g, was installed. It uses a CdZnTe (Cadmium Zinc Telluride) detector which is sensitive to γ radioactivity ranging from 30 keV to 3 MeV [8], and can be used at normal room temperature. The set-up of the device on the robot is explained in Section III-B.

III. DEVELOPMENTS CARRIED OUT

This section describes the work carried out on H@RI to make it into a robot-operator able to intervene in a nuclear environment. Firstly, the motherboard and the operating system were modified in order to manage all the developments which were to be made to the robot (Section III-A). Next, the gamma spectrometry detector set-up is briefly explained (Section III-B). Control of the platform was organized in three ways : H@RI's walking is controlled via a video game joystick (Section III-C.1) whereas its arms reproduce the movements of a remote-handling operator who uses a deep field camera (Section III-C.3), and the grips at the end of the robot's arms are commanded via an instrumented glove (Figure 1).

A. OS, hardware et middleware

The original motherboard's memory limited the amount of data which could be stored on it. One of the first jobs was to replace it with a Odroid XU3, a central processing unit Samsung Exynos5422 with 2 GB of RAM. The memory

can be adjusted with 16, 32 or 64 GB sizes. Maintenance of the Ubuntu 9.10 version of the operating system stopped in April 2011. This limits the possibility of software updates and therefore motivated the move to a Lubuntu 14.04 type Linux version, for which maintenance is planned to continue through to April 2019. Moreover, its light operating environment is well-adapted to this project, particularly as concerns the energy consumption and a RAM mobilization lower than the classic Ubuntu version. The framework offered with the DARwIn-OP robot is specifically linked to this humanoid platform, making it difficult to transpose developments between different platforms. Today there are a large number of proprietary or open-source middleware, for example ROS, MOOS, OROCOS, etc. The Robot Operating System middleware (ROS), based on an open-source sharing mode, is currently widely used in the robotics field, and enables external developers' contributions to be shared [9]. ROS can be viewed as a set of interconnected programs or nodes, making up a robot operating system. It also offers a standard communication between the different programs and associated programming languages. Deciding on this middleware for our project thus made fast, flexible integration of developments possible on different platforms [10]. During the change of the open-DARwIn-SDK framework to ROS, it was necessary to create ROS kinematics control nodes for H@RI. Instead of creating the node from the open-DARwIn-SDK framework, an equivalent node developed by the Institut de Robòtica i Informàtica Industrials (Barcelona University), was able to be used [11].

B. Nuclear instrumentation

H@RI had to be able to carry out gamma spectrometry measurements in order to determine the radionuclides present during operations in a nuclear environment. Given that the robot is only « baby-size », the dimensions of the detectors used had to be in proportion. It was decided to attach the detector onto H@RI's head to avoid any disturbance of the robot's overall kinematics, like its walking or arm movements. The GR1 detector was held on the humanoid's head by a support created via a 3D printing technique (Figure 2). Section IV-B gives an example of acquisition using this

detector.

C. H@RI robot control

Remotely-handled control of H@Ri takes place in two steps, either through piloting the robot's legs to position the humanoid (Section III-C.1), or by piloting its arms (Section III-C.3) and grippers to carry out a task (Section III-C.1).

1) Walking control: A video game controller is used for this. It has two joysticks, one controlling forward and backward movement, and the other the robot's rotation on the spot. The control device is also used to switch between control of the legs and of the arms. Though walking could also be controlled via a computer keyboard, the game controller approach was preferred here, given that the operator must be facing the deep field camera used to control the arms (Section III-C.3).

2) Arm control: A motion capture method using an ASUS depth camera was suggested as the means to control the humanoid's arms. The objective was to be able to handle H@RI remotely, without having to set up an operator with instruments. In this case, the operator's movements are the equivalent of a man-machine interface. This contact-free piloting method is an intuitive way for an operator to control H@RI's arms.

3) Gripper control: Controlling the robot's arm by deep field camera makes the simultaneous use of a joystick impossible. This is why H@ri's grippers are piloted via instrumented gloves. The gloves enable an intuitive control of gripper opening and closing, proportional to the curve of the operator's fingers.

IV. TESTS

This section illustrates the different tests carried out with the H@RI robot in its condition as delivered by ROBOTIS. Section IV-A describes the irradiation tests performed on the robot's sensitive components. Next, the validation tests for the GR1 detector setup using calibration radioactive sources are presented (Section IV-B). Lastly, tests were made to validate the use of a depth camera to remotely control H@RI's arms (Section IV-C).

A. Tests in irradiator

A key point which had to be checked regarding the use of a robot in a radioactive environment is the on-board electronic components' resistance to ionizing irradiation. Because of the damage which can be caused by irradiation, it is necessary to estimate the maximum admissible dose for these electronic components. Knowing this maximum value is important in order to be able to estimate the reliability and the performances to be expected from the system in irradiating environments. The ionizing γ radiation emitted by radioactive elements is the subject of special attention. In this particular situation, penetrating-type radiation cannot be stopped by heavy, bulky shielding. This meant the consequences of the interaction of this irradiation on the electronic components had to be evaluated. This impact can be assessed by measuring the total absorbed dose, representing the energy

deposited in the material. This total absorbed dose represents the effect of the irradiation, the most important property for robotic systems working in irradiating environments. The hardening of electronic components depends on the technologies used, the manufacturing process or the complexity of the electronic board's sub-systems. A distinction can be made between components specially hardened during their manufacturing and off the shelf components (non-hardened). Nevertheless, the irradiation resistance capability properties of certain commercial components equivalent to especially hardened components could be noted. To our knowledge, there were no data concerning the DARwIn-OP robot's electronics behavior under γ irradiation. It was therefore decided to carry out tests in a Cobalt-60 irradiator in order to forecast this behavior and estimate the vulnerability of the on-board electronics. In this type of test, the energy deposit simulation is done in a panoramic irradiator equipped with a Cobalt-60 source. The position within the bunker enabling the desired dose rate to be reached was evaluated by simulation with the RayXpert software (Figure 3). The H@RI robot's electronics components tested were :
- PC2i adaptor,
- CM-730 controller,
- Interface board,
- Power supply board,
- Head board.

As well as these electronic components, the on-board detectors also have to function well. For the H@RI robot, the consequences of γ radiation were analyzed on the following items :
- Loudspeaker,
- HD 2MPx camera,
- Two ventilators,
- Accelerometer,
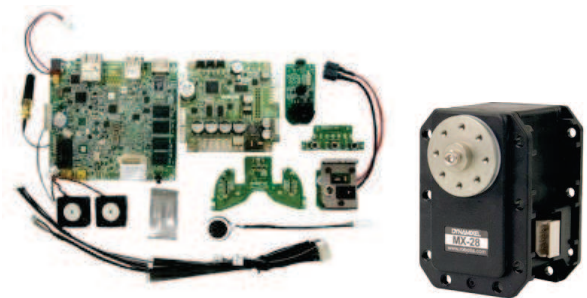- Gyroscope,
- MX-28T servomotor.

Fig. 4: Electronic component kit (left) and MX-28T servomotor (right)

The MX-28T servomotors are used as actuators and have a digital memory whose functioning under irradiation had to be checked. The behavior of metallic or insulating materials was not considered in this case, as the energies under which alterations to their properties have been observed are in the several thousand Gray dose range. The component irradiation was carried out in order to simulate a total accumulated dose
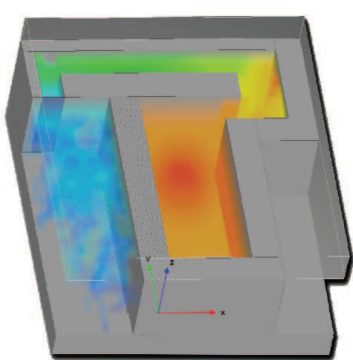
Fig. 3: Cobalt-60 irradiator : dose rate simulations by Rayxpert (left) and view inside the bunker (right)

Accumulated dose level (Gy)	0	5	10	15	20	33	44	53	67	82	87	101	121	136	232	330	428	525	623	720	832	916	1024
Bunker temperature ($^\circ$C)	19	19	19	20	20	20	19	20	20	20	19	20	21	21	21	21	22	22	22	22	22	22	22
Dose rates (Gy.h^{-1})	0.21														0.6								

TABLE I: Irradiation levels

of 1024 Gy at a temperature set at 20°C. The irradiations were performed with a dose rate of 0.21 Gy.h^{-1} up to 136 Gy, then 0.6 Gy.h^{-1} up to 1024 Gy. The irradiation profiles are summarized in Table I. The components were polarized during their irradiation, in a similar way to their normal use in the humanoid platform. A methodology was then implemented to test different functions of the H@RI robot PC2i adaptor, such as the USB port, the video output, disk writing, the Ethernet port, and the Wifi. The tests were repeated at each irradiation level, as shown on Table I, until a failure was observed. When a failure was detected on one of the components, it was replaced in order to continue the irradiation of the other components. A test procedure was implemented to evaluate the condition of the components at each irradiation level. These tests were :

1) **Camera** : A photo was taken within the bunker in light, and a second photo after positioning an opaque screen in front of the lens.
2) **Ventilators** : These were started up to be able to visually check their functioning.
3) **Microphone, loudspeaker, USB, disk writing, network access (Ethernet, Wifi)** : Ubuntu operating system test procedures were launched to check that each sub-system was functioning correctly.
4) **Accelerometer and gyroscope** : A writing procedure for the data sent by the detectors was launched. The test involved checking whether the detectors were able to send back the values.

The accumulated doses observed at failure for all the sub-systems tested are summarized in Table II. The accelerometer as well as the gyroscope was tested via the CM-730 controller. As the servomotors continued to function up to a dose of 1024 Gy, the irradiations went on until failure, which

Sub-system	Accumulated dose (in Gy)
PC2i Adaptor	200
CM-730 Controller	300
Head board	1014
Ventilators	200
Loudspeaker	430
2Mpx HD Camera	200
MX-28T Servomotor	1400

TABLE II: Accumulated dose measured at sub-system failure

occurred at a dose of 1400 Gy. Based on this work, it is estimated that H@RI can function up to a total accumulated dose of 200 Gy (failure of the PC2i adaptor and of the HD camera).On nuclear facilities undergoing dismantling, particularly in high level cells, the reference dose for the development of complex systems is 0.1 Gy.h^{-1} [12], i.e. 2000 hours of work for the H@ri robot. As a comparison, this dose would represent 10 years of work for a human operator under the terms of French regulations. This limit has been qualified for an environment where only gamma radiation is present. As previously indicated, the components in question were not designed to be irradiation-resistant. For statistical purposes, it would therefore be necessary to carry out a sufficiently large number of tests to determine the level of irradiation resistance and the associated confidence level.

B. GR1 Detector Test

Tests were carried out in order to validate the GR1 detector set-up on the H@RI robot. Standard radioactive Cesium-137 and Europium-152 sources were used for these experiments. This type of source is commonly used in laboratories to test the functionalities of measurement detectors. For these

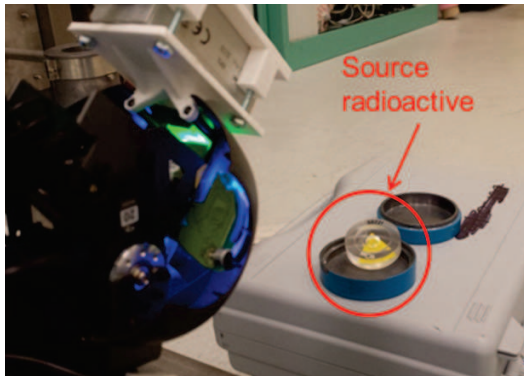trials, the H@RI robot was equipped with a GR1 detector and placed facing the standard sources (Figure 5).

Fig. 5: H@RI facing a Cesium-137 source during the acquisition

| Source	Césium-137	Europium-152
Distance from the source (cm)	30	20
Acquisition time (min)	5	3
Number of counts (net area)	9556	58962

TABLE III: Acquisition characteristics

The spectra from each of the sources were analyzed to qualify the integration of the gamma spectrometry line (Figure 6). The characteristic lines for the radioactive elements used are clearly found : 662 keV for Cesium-137 and (121 keV, 244 keV and 3444 keV) for Europium-152. This experiment validated the installation of the GR1 gamma spectrometry detector on the H@RI robot. The analysis result shows that the gamma spectrometry line set up in the robot's architecture did not lead to any deterioration in the quality of the spectra : resolution and yield.

C. H@ri robot control test

A final test consisted in simulating an operation where the H@RI robot had to move to position itself facing a surface from which it had to collect a swipe sample. This test was representative of missions which can be needed in contaminated environments, to check the loose (non-fixed) surface contamination. A swipe sample is an efficient, easy way to collect samples from radioactively-contaminated surfaces. During any intervention in an irradiating contaminating environment, the personnel must wear full appropriate P.P.E. Radioactive contamination involves a process leading to a radioactive product being deposited on an object or a living being. Contamination is a phenomenon which is distinct from that of irradiation (see Section IV-A). Thus in order to be able to handle a swipe sampling disk, a device was attached to one of robot's grippers, onto which the swipe was attached. When a contamination risk has been identified, the regulations impose vinyl coveralls to equip any intervening personnel. This approach was kept in mind and
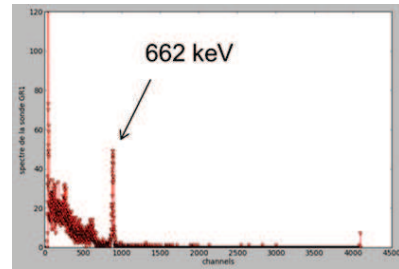
(a) Césium-137
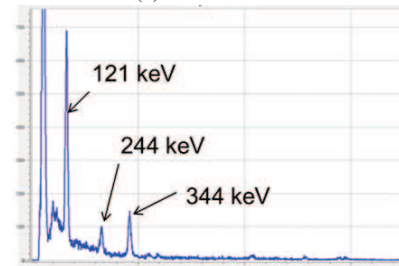
(b) Europium-152

Fig. 6: Gamma spectra - GR1 detector on board H@RI

the H@RI robot was suitably equipped to prevent any possible contamination (Figure 7). The humanoid's movement within the work zone was managed using the joystick via a WiFi communication. The addition of the GR1 detector on H@RI's head seemed to disturb the center of gravity of the platform, which led to a posture error and thus to instability in walking. To prevent any tipping forward during a movement, the robot's feet were simply lifted in order to compensate for this imbalance. Obviously, it will be necessary to set up a stabilizer which will take into account the data from the gyroscope, accelerometer and other force detectors. This stabilization algorithm will enable the robot to compensate for the impact of the addition of an additional weight. The second phase of this experiment was to carry out the swipe sampling on a tank representative of the equipment found in a nuclear facility. The H@RI robot arm piloting in the work zone was managed by a remotely-located operator. This operator mimed the movements needed to carry out the swipe sampling and the body movements were scanned using an ASUS depth camera, then reproduced by H@RI. Figure 7 illustrates how this sampling was carried out. As can be seen, the operator is separated from the intervention site by a vinyl air lock (Figure 7c) commonly used in the nuclear field to ensure containment of any contamination. This experiment is a good illustration of the robot's ability to replace a human for an intervention in an extreme environment. As this test case did not require the use of grippers, tests of the instrumented glove were carried out separately and proved to be satisfactory. It was shown that controlling a humanoid robot can be a solution for a large number of tasks without needing a specific design for each of the missions it will need to perform. In other words, the humanoid robot appears to be a good alternative to the development of specialized robot, as has been the case in the nuclear field.
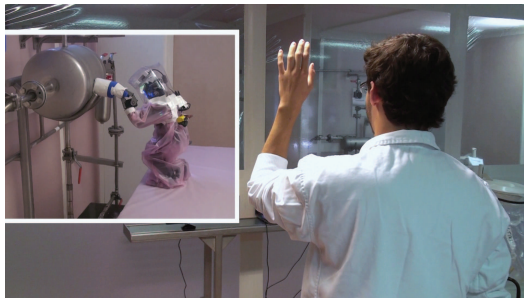
(a) Moving towards the work zone

(b) In position to collect a swipe sample

Fig. 7: H@RI robot dressed in vinyl coveralls

(c) Operator using his arms to mime the swipe sample collection.

(d) H@RI reproducing the operator's movements.

Fig. 7: H@RI robot controlled by operator movement capture to carry out a swipe sample collection

V. CONCLUSIONS

The use of a small-size humanoid, DARWINOp, as an assistant in a nuclear environment to carry out different tasks (investigation, cleanup) [3], has been demonstrated. The result was obtained firstly by including a gamma spectrometry line in the robot for the radiological characterization of its environment by direct readings or by sampling. Secondly, motion capture was used on the body movements of a remotely-located operator for arm control and the development of a containment suit for the robot and irradiation trials (resistance : 200Gy) all contributed. The combination of the innovative controls offered here, very operator-friendly, improves the remote handling aspects, in particular for cleanup operations which require delicate manipulations. The integration of the system and the development of new functions in the ROS ecosystem were also a success, proven by the general nature of the tasks carried out. At this stage, the applications of this work can be imagined extended to more complex conditions of use, in particular in zones where the floor is cluttered. In this perspective, the robot's stability problems when moving need to be taken into account, as they can interfere with the H@ri robot's approach to the intervention zone where it has been shown to excel. Thus the utilization of anthropomorphic systems for D&D is a support for work on improving the reliability of humanoid movement in extreme environments. Moreover, other lines of study are appearing to meet the need to adapt robots to such environments. In particular, these include dealing with aspects like robot contamination or of improving the humanoid's dose resistance to better withstand extreme conditions.

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