ROBOTIC ARM CONTROL IN EVA SCENARIOS

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ABSTRACT

The application scenario to which the study is oriented is focalized on Moon-Mars human exploration missions where interactions are mainly conceived as human robot collaboration and where the actors involved cooperate in the same environment and towards common goals.

More in details, in this study we've analyzed the problem of moving a robotic arm by an astronaut in Extra Vehicular Activity (EVA) without the usage of common control systems. Typical control interfaces like mouse, keyboard and joystick, are not easily usable, since the astronaut is in an open environment and cannot carry around all the devices needed. Moreover, his suit and his gloves are hindering his movements, so the accuracy of the controlling would be very low, and precision is a very critical issue of the desired interface. With respect to these constraints we have developed an interface we've named "Ubiquitous Arm (UA)", for moving and controlling the robotic arm with the tracking of the astronaut's arm, wrist and hand itself that does not count on optic technologies. In particular, linear accelerometer technology has been considered for the tracking requirement and data gloves have been utilized to realize discrete signal communication through hand gestures recognition. The combination of these two technologies allows the realization of the final UA interface. The visualization and selection of the different parameters and commands related to the UA interface have been furthermore integrated into an

Augmented Reality GUI able to trigger interaction from visual targets placed on the objects and display graphical information directly over-imposed on the real world. The UA system grants an overall solution to robotic arm movements and operations, since association is made with the end effectors and not according to joint configuration; assuming a proper inverse kinematics solution, each robotic arm can be moved no matters how many degrees it has and dimensions it consists of.

1. INTRODUCTION

Human-Machine Interface (HMI) can be shortly defined as the field where people and technology meet. This study is performed on HMI aspects having the aim of developing advanced immersive Human-Machine Interaction devices/methods allowing the users to locally/remotely monitor and command robotic systems through innovative and easy to learn/use interaction devices. The work described in this paper is about an HMI system realized within the STEPS “Sistemi e Tecnologie per l’EsPlorazione Spaziale” research project funded by Piedmont region with the participation of the “Fondo Europeo di Sviluppo Regionale” and led by Thales Alenia Space Italia.

The STEPS project aimed at studying existing technologies and analyzing new solutions for spatial exploration that, with a highly growing trend, involve both human and robot presence. The STEPS Human-Machine Interface (HMI) work package study had two different but conjunct aims. The first aim was to develop HMI devices permitting, among other things, the local/remote control of rovers equipped with robotic arm. The second aim was to enhance the user capability to control the system through the provision of tools designed to augment the decisional and planning capability of the operator and increase as well system autonomy in order to allow humans a greater supervision instead of execution role. This HMI was conceived as human-robot collaboration, where the actors involved cooperate in the same environment and towards common goals. The following schematic shows the overall HMI system general architecture.

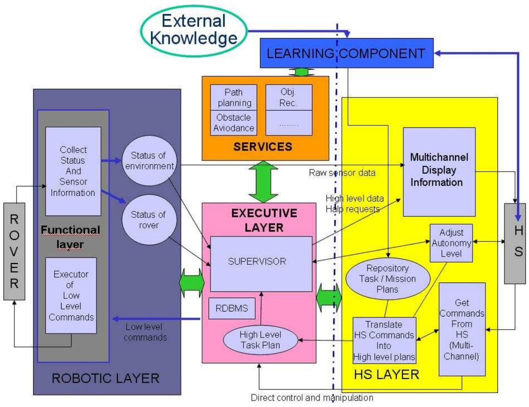


Figure 1 – HMI system general architecture

In this architecture the "HS (Human Supervisor) Layer" provides the Human with the robotic system monitoring and control functions; the "Executive Layer" establishes the sequence of actions to perform for reaching a set of goals according to the current system autonomy level; the "Services" block contains various and specific applications (e.g. path planning, visual tracker,…); the "Learning Component" exploits system external knowledge for supporting the user during the execution of procedural tasks; the "Robotic Layer" represents the physical robotic system itself and all layers are connected to each other by means of a common "Communication Layer".

Coming back to the HMI work package first aim, we've analyzed the problem of moving a robotic arm by an astronaut without the usage of common control systems, as keyboard, mouse, joystick / joypad, and optic systems. Astronaut suits and gloves in EVA typically hinder the user movements and decrease the fingers precision; moreover, we'd like the astronaut to be able to move freely in his/her task without carrying around any external control device.

In the considered scenario, an astronaut is doing some tasks in EVA on a planet surface. Tasks to accomplish are for example the assembly/repair of some mechanical and/or electrical devices, performing of experiments on resources found on planet, carriage of some objects. A robotic arm, mounted on a four wheels rover, is provided to help the astronaut in his/her mission.

With respect to these requirements, we've studied what kind of interface and hardware could satisfy such requirements and we've analyzed how to create an intuitive and easy-to-use teleoperation guidance system.

We have developed at the end an interface for moving the robotic arm with the tracking of the astronaut's arm itself that does not count on optic technologies. In particular, linear accelerometer technology has been considered for the tracking requirement, and data gloves have been utilised to realize discrete signal communication through hand gestures recognition. This interface has been named "Ubiquitous Arm (UA)" due to its capability to be carried everywhere since it can be completely embedded into the EVA suit. The desired guidance system satisfies many requirements, high accuracy of movements, customizable factor of scale in the drive, overall intuitive system that minimizes training for users/astronauts, not invasive technology that can be on the astronaut suit, it does not deal with any external control devices and finally, it works by dead reckoning inertial process so that it doesn't need any external reference to work. A variety of end effectors control functions (e.g. pitch and roll orientation; gripper opening / closure; ...) and rover navigation controls have been additionally implemented through the translation of the user wrist orientation and hand gestures recognition.

Moreover, for making the astronaut able to monitor the settings of robotic arm parameters like as instance the scale factor or the axes gain, the astronaut has been provided with a Graphical User Interface (GUI) realized using Augmented Reality (AR) technologies integrated into the EVA helmet.

2. THE UBIQUITOUS ARM (UA) SYSTEM

The Ubiquitous Arm is a human/robotic multimodal interaction device composed by data glove and 3D inertial sensor devices aimed at manually controlling and commanding the spatial positioning of robotic arm' end effectors and relevant functions.

Data glove input commands are generated through the conversion of analogue input generated by finger flexure into digital discrete signals. Fingers configuration is then interpreted in a way that specific user hand metaphoric gestures are traduced into specific commands to the system. These commands are utilized both for setting system parameters and variables as well as for controlling tool change and actuators functionalities.

Beside this first interaction' modality realized through data gloves and employed for imparting discrete commands, a second interaction' modality, in tight conjunction with the previous, is utilized for the purpose of commanding and controlling the robotic arm end effectors spatial position. The user hand relative spatial movements is tracked by 3D inertial transducers whose signal, after appropriate elaboration, is converted into trajectory and coordinates settings for the arm' end effectors positioning.

UA Functional architecture

Discrete commands (generated by the user fingers gestures) and relative positions (extrapolated from 3D accelerator signals located at the user arm and hand) will be elaborated and converted into High Level commands, will pass through the Human Station for finally reach the Robotic Layer for commanding robotic arm movements and actions.

The system is in charge of interpreting and managing crew instructions, provided by fingers configurations,

into relevant robotic arm commands (start moving; change gain level; stop getting relative positions; open actuator clamp; ….).
On the other side the Robotic Layer (or one of its service component) shall be in charge of controlling the position of the robotic arm actuator (adopting inverse kinematic algorithm) in order to follow and reach the X, Y, Z positions extrapolated from accelerometer transducers' signals.
The final result of this one-way interaction system (from user to device) can be perceived as follow:

- the robotic arm actuator reproduces, with some (but almost negligible) delay due to the computational and transmission chain in between, the movement/s performed by the operator arm
- the discrete functions of the robotic arm as well as system parameters settings will be commanded by the user fingers' configuration.

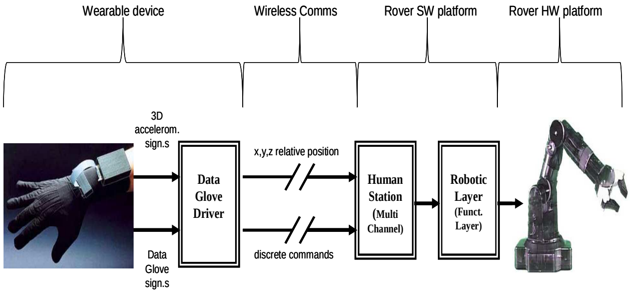


Figure 2 – Ubiquitous Arm Functional Architecture

UA Demonstrator hardware devices

The UA demonstrator developed during this project has been realized using the following hardware: three Xsens Mti and Mtx miniature inertial measurement units with integrated 3D magnetometers (3D compass); one Xbus Master device interconnecting the motion trackers data to the laptop through wireless Bluetooth link; one 5DT wireless Data Glove; one X-Bee wireless module and one ZigBee dongle; one LynxMotion A4WD1 Robot Kit Rover equipped with a AL5B Robotic Arm Combo Kit; one PC laptop running the UA control software.
In order for the EVA crew to be constantly equipped with data glove and the accelerometer devices, it has been foreseen, for the final system exploitation, to embed these interaction devices directly into the EVA suit while the electronic devices for data glove / accelerometers control and for relevant data elaboration and transmission has been foreseen to be located in the EVA crew suit backpack.
In principle anyway, for a suitable architecture of the operational system, it would be preferable having the computational device, that can be easily miniaturised, located at the user site (wore by the EVA crew).

UA Data communication

Communication between the EVA crew (user site) and the rover site shall be wireless (at least for the final functional system) and shall transmit to the Rover Layer X,Y,Z relative positions as extrapolated from the 3D accelerometer and, at the meantime, discrete commands generated by means of crew finger gesture (following metaphoric predefined fingers configurations). The communication between the EVA crew and the rover and/or arm is made using the ZigBee protocol implemented over the XBee radio-module hardware. ZigBee protocol has been used has due to its properties of low-power consumption, this property is of fundamental importance during the scenario hypothesized.

UA multimodal interface development

Concerning the development of the UA multimodal interface, we have focused our attention on searching new and intuitive ways for robot controlling and commanding: our goal thus was to provide an interface that allows an astronaut, or more generally a user, to easily control a robotic arm. The combination of two technologies, linear accelerometers for realization of the tracking part and a data-glove for communicate discrete commands allow the realization of the final interface envisaged in our original concept.
First the tracking system has been realized: accelerometers are mounted directly on user's arm, and the computation realized on the devices output leads to the position, hence the movement, of user's hand.
Each turn, of which the length is given by sampling frequency of the devices adopted, the movement is determined by a process of dead reckoning on the previous data acquired. Clearly the sampling frequency is a critical feature: if the frequency is not high enough the movement reconstructed can be very misleading. The Mti and Mtx accelerometer devices we have utilized for our demonstrator grant a sampling frequency of 100 Hz, high enough for our scenario.
As said each turn the hand of the user is tracked by using accelerometers outputs; starting from an initial position, the movement is directly computed each sample data received.
The tracking system consists of three linear accelerometers; two are mounted in the center of the two arm segments, as shown in the next figure, while the third one is directly placed on the back of the hand.

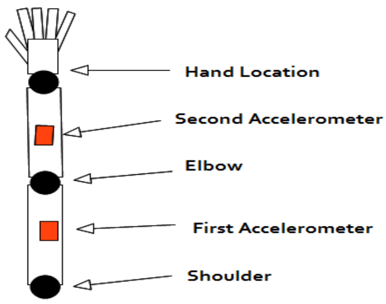


Figure 3 –Accelerometers position on the arm

First two accelerometers are used for tracking the end part of each segment using the orientation output that they provide.
The first accelerometer is responsible of computing the position of the elbow; the length of the arm is expressed in three-dimensional coordinate system, since the distance between the shoulder and the elbow is known a priori. The orientation of the gyroscope returned by the device allows the rotation of this vector, hence the determination of the elbow point in the three-dimensional coordinate system adopted. The solution found is similar to the problem of finding a point on a sphere surface knowing the center, the radius, and the angle, calculated from a fixed starting point. The radius of such sphere is the length of the arm segment, the center is the shoulder, and the angle of inclination is returned by the gyroscope of the accelerometer.
The same procedure is realized with the second accelerometer, mounted on the center of the forearm. The length of the segment is known a priori as before, and it's measured from the elbow. The output angle gives again the inclination again and, once rotation is applied, the end of the segment is computed for finding the wrist and the hand.
The hand position found in this way it's expressed in terms and reference system of the forearm; the orientation and the position values depend on elbow inclination with respect to the first segment of the arm.
In order to obtain the final position of the hand, the two computations described are merged together; the elbow reference system (including the hand position computed) is expressed in terms of shoulder reference system. The two rotations are hence combined to determine the hand position starting from the first joint of our arm, the shoulder.

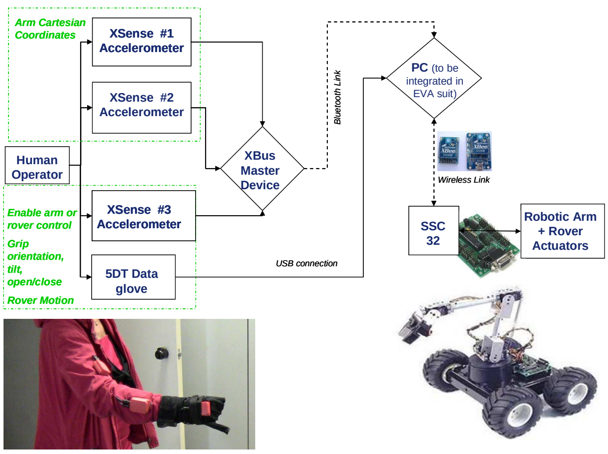


Figure 4 – UA functional scheme

This solution does not involve linear accelerations provided by accelerometers that would introduce complete drifting. The method adopted raises from the consideration that movements of human limbs are realized through rotations instead of linear accelerations, since constrained by the joints.
The precision of gyroscopes mounted on linear accelerometers is very high, and grants accurate results during all the tele-operation. In details, angular resolution corresponds to 0:05 degree. The resulting accuracy is much higher to the one derived from the computing of linear accelerations, especially when dealing with very slow movements, that are not even detected otherwise.
The efficiency of the tracking is also granted for the whole duration of the task, while the dead reckoning of linear accelerations is highly dependent on the execution's length over time.
Beside the control of the end effectors space position, it has been also implemented the control of the end effectors pitch and wrist rotation and gripper opening/closure.
For a proper control of these joints, we have decided to implement an exclusive selection of type of motion.
The movement of these joints has been realized through a third accelerometer mounted directly on the back of the hand as depicted in the next figure.

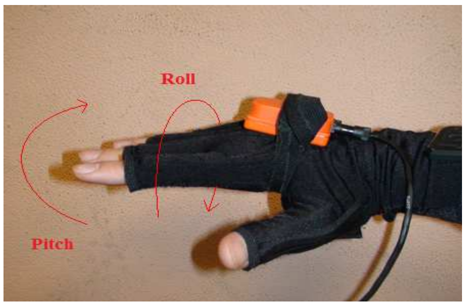


Figure 5 – Arrangement of third accelerometer

This accelerometer plays another role with respect to the others previously described; it expresses the rotation of the wrist and does not contribute in tracking the position. This feature allows us to move the end effectors not just in terms of position but also in rotation. For example user can perform (un)screwing operations through the usage of the robotic arm directly rotating his wrist; this shows how intuitive the interface may be in dealing with common tasks, without any unnecessary user's effort in controlling.
The third accelerometer's output is directly associated to the robotic arm and in particular to the end effectors orientation. This configuration enables a direct control of the end effectors by the user since the inclination of human hand directly corresponds to the input given to the robotic arm. The tele-operator can (un)screw directly using his/her hand. Clearly, since the interface is realized with a programming language, control of scale factor is always feasible. Rotation of the wrist can have a different resolution with respect of end effectors' one. Very accurate tasks that deal with very small angle changes can hence be performed by wrist rotation of the user's hand. Two angles are determined by the third

accelerometer, pitch and roll. These two rotations are the typical DoF of the end effectors.

Figure 6 – UA system test

UA provided solutions and further development

The robotic arm guidance system realized by TAS-I during this research project has been able to provide valid answers to all the requirements initially defined for this type of human-machine interaction device. Some of the major requirements fulfilled by the UA system are: prompt execution (possible minimum delay is not perceived by the operator), high accuracy of movements, customizable factor of scale in the drive, overall intuitive system that minimizes training for users/astronauts, not invasive technology that can be placed on the astronaut suit, it should not deal with any external control devices as mouse, keyboard and similar, and should finally work by dead reckoning inertial process, since no external reference can be measured in the planetary exploration utilization scenario.

The solution adopted for the breadboard provides moreover several additional advantages as the low material / production costs (the interaction device total cost for the demonstrator is in the order of 1 – 2 KEuro); a high capability for the system to be configurable in order to be adapted to a variety of users preference as well as applied to several and diverse tasks / type of operations and, last but not list, an elevated spin-off capability for ground applications as instance in the industrial and medical fields.

Several additional developments have been envisaged for improve or extend the UA basic concept developed during this research project so to implement new space as well as ground applications. Some of them are: video feedback utilized for the end effectors remote control and commanding; autonomous performance of structured tasks through the adoption of the imitation learning model; tactile haptic feedback in order to introduce control of the measure of grasping in an even more intuitive way; the tracking system can also be used for guidance of the rover on which the robotic arm is mounted (leaning the user wrist forward and backward would change the rover speed amplitude, negative and positive, and lateral rotations would correspond to curves); ….

3. The GUI in augmented reality

In order to allow the astronaut to monitor and control the mission supporting systems at any time and contemporaneously move freely in his/her task without carrying around any external device, an immersive Graphical User Interface (GUI) unit that uses Augmented Reality (AR) functionalities has been designed. Information to be presented to the astronaut is expected to be directly projected on the helmet visor of the EVA crew so to augment his/her knowledge of the real environment with the relevant textual or graphical data. During the STEPS project a GUI-AR demonstrator has been developed and integrated with the UA user interface so to provide the user with a complete ubiquitous and wearable command and control device. Different GUI elements and functions have been developed in this demonstrator which allows the user as instance to manage scientific experiments using rover instruments; receive information about mission and operations status; manage a 3D map; monitor rover and environmental data; manage the setting of the resources.

The GUI-AR demonstrator

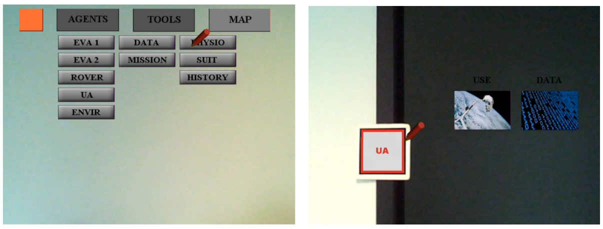
The immersive GUI demonstrator has been composed by an acquisition camera device grabbing images at 30 Frame per Second (FPS) at 640x480 pixel resolution. A marker based tracking technology has been then used to extract objects position and orientation.

Figure 7 – The marker based objects position and orientation

Interaction with the overlaid data is achieved with a wearable finger mouse while the head movements, detected thanks to a 6 Degree of Freedom (DoF) gyros device, has been used to hide/show GUI elements out of the user Field of View (FOV). The display device is a Head Mounted Display (HMD) with 1024x768 pixel resolution and can be worn also with eyeglasses. Even if low cost equipment has been used, the system is ready for high-end See-Through devices too.

Figure 8 – Head Mounted Display and 6DoF Gyros

In order to maintain the EVA's FOV as clear as possible different strategies have been studied for presenting the information. Most of the functionalities can be recalled by the user through the head movement; raising the head will show up an actions menu, while looking right will provide contextual data.



a) b)

Figure 9 – Data a) recalled with the head movement – b) overlaid near the tracked object

At any time the EVA can look at its wrist to know agents position on the map or read incoming messages. Other information, strictly connected with Agents, is only available when the EVA looks at them.
Data are then presented to the EVA crew in three different forms:

- Data outside EVA's FOV that can be recalled only with head movements
- Two dimensional data overlaid nearby the tracked object
- Three dimensional maps aligned to user wrist

Figure 10 – Finger mouse and 3D map on EVA writs

GUI-AR Considerations

The system has been designed keeping in mind the real-time constraints of an immersive GUI. In order to keep the usability and user friendliness of the GUI the system provides frame rates near to 30 FPS and interaction response times around 40 ms. Tracking technology resulted to be quite stable considering the low camera input quality and the reduced size of markers. There is nevertheless to point out the fact that the demonstrator realized during this project has the only aim to demonstrate the concept feasibility and test the relevant functions. For an EVA space exploration scenario the hardware to be utilized needs of course to be modified and customised to the crew EVA suit.

4. CONCLUSIONS

Both UA and GUI-AR demonstrators have been tested by users that were completely external to development phase with great results; as desired the system is very intuitive and training time is reduced to little initial information. The direct visual feedback of the UA working area provides all the control needed for the execution of most robotic arm manual tasks foreseen in our user scenario while images of the working area provided by a camera mounted on the end effectors can provide a suitable feedback for the execution of more accurate operations.
The UA system grants an overall solution to robotic arm movements, since association is made with end effectors and not according to joint configuration; assuming a proper inverse kinematics solution, each robotic arm can be moved no matters how many degrees it has and dimensions it consists of. This approach doesn't lead to any disadvantage since in our scenario there's no interest in obtaining robotic movements that are similar and correspondent to human's ones.

5. ACRONYMS

AR	Augmented Reality
DoF	Degree of Freedom
EVA	Extra Vehicular Activity
FOV	Field Of View
FPS	Frames Per Second
GUI	Graphical User Interface
HMD	Head Mounted Display
HMI	Human Machine Interface
IVA	Intra Vehicular Activity
SW	Software
TAS-I	Thales Alenia Space Italia
UA	Ubiquitous Arm
VR	Virtual Reality

Table 1- Acronyms Table