2013 IEEE RO-MAN: The 22nd IEEE International Symposium on Robot and Human Interactive Communication
Gyeongju, Korea, August 26-29, 2013

A Novel Human-Machine Interface for Working Machines Operation

Matteo Tanzini, Paolo Tripicchio, Emanuele Ruffaldi, Guido Galgani, Giovanni Lutzemberger and Carlo Alberto Avizzano

Abstract— **The future of working machines winks to semi autonomy and latest technological aids to improve the quality of operations as well as the easiness of specific tasks execution. This field can take great advantage of latest human-machine interface (HMI) technologies that has been applied in the last years in field like virtual environments and robotics.**

The present paper discusses a novel approach for interactive operation of working machines. The approach combines traditional controls with visual/vision and haptic interactions. A wearable projection system has been introduced with the purpose of describing a wide set of localized commands recognized by the system's vision module.

A preliminary setup has been developed using a simplified demonstration platform.

A test session applied to a manipulation robot is presented to evaluate the performance of the proposed solutions in terms of task effectiveness, neglect tolerance, interaction effort and usability of the human-machine interface.

I. Introduction

In the last decade, teleoperation and partial autonomy began to be a reality in the working machine industry. Teleoperation can already be found for example in the mining, construction and demolition machines. The 13% of the 25,000 units of robots installed up to the end of 2004 are construction and demolition robots [12].

In the recent industry spot, decline of productivity and pay-ability are deepened by skilled worker's lack and problem of safety [14]. When working in environments, that could be dangerous, poor or hard to reach for man, teleoperated robots can act as the extension of human bodies and strength their ability in terms of perception and operation [13]. An automated machine can be very productive, and can perform tasks faster and more accurately than humans can.

To date, machines lack is human reasoning, such as the ability to adapt to new situations, react to exceptions, reason on situations or plans as a whole.

Limited to the level of today's artificial intelligence, it's unrealistic for a robot to work safely and effectively all by itself in a construction or demolition field. So, the robot development direction has changed from autonomous mode to human-assisted mode.

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Thus, the development of a teleoperated control for an operating machine perfectly fit the solution. Combining human's intelligence with robot's autonomy flexibly forms the current mode of teleoperation system.

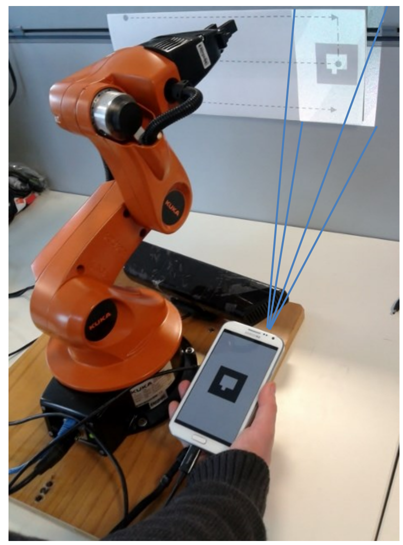

Figure 1. Projector operation example. The user instructs the system about the task to be performed by means of a portable projector interface. The system recognizes the projected marker and reconstructs the task phases to be accomplished.

Actually, in the worldwide scenario of working machines there are some companies, like Husqvarna, Brokk, Finmac, who have successfully introduced some teleoperated demolition robots: these machines can be of various powers and dimensions and all of them rely on the presence of a human user in their proximity. The supervisory control and the related human-machine interfaces are still rather primitive. Operators use joysticks or levers to control the movement of the machine's arm like they were performing from the inside of the cockpit.

Current hydraulic manipulators are often operated using individual joint control. Since many of these manipulators are long kinematic chains, such as excavators or demolition vehicles, it can take years of training and experience to become an expert operator, resulting in a large number of novice operators. A coordinated control (the ability to control the machine using an operating device whose segments resemble the manipulator geometry) has been shown to improve various operator performance measures [16]. In everyday use, it can be desirable to have the operator off the manipulator so that he can have a better viewpoint. Having the input device and the manipulator only electrically

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connected creates greater freedom of design for input devices.

This paper focuses on the introduction of novel human-machine interfaces for working machines operation using standard robotic interaction features. In particular the next section introduces some interesting works from literatures that are related to this topic.

Together with the development of an ad hoc interface for a real working machine we decided to build a testing platform to assess the real benefit of this approach for the machine users.

A multi-modal interactive framework that allows the control of a mobile manipulation arm through the coupled use of visual and haptic information is presented. In our approach a worker is provided with a portable projection system capable of wireless communication, while a sensorized remote platform uses computer vision algorithms to receive operational commands.

In section III, we will present the performance attributes we focused on during the concept design phase and the human-machine interface testing platform including the basic design and its operating modalities. In section IV we will provide some details on a possible implementation, including a hardware and a software platform that benefits of currently available robot-operating-systems. The setup of experimental test sessions is described in section V with the purpose of assessing the performance attributes of the test system with the new human-machine interface to obtain the specifications for a final system operating on a real working machine. Results of a preliminary performance test are described in section VI while section VII presents the main conclusions of the paper and the future activities.

II. State of the art

In literature many novel approaches for human computer interaction have been proposed in the last years, for instance adopting human forces directly captured from the users arms as input of a virtual interactive simulation [1].

However these new paradigms have been extensively applied in the field of virtual reality [15] and simulation and few have found success in the context of working machines.

In this specific field we can find various application of coordinated control. Schwarzmann and Hayn in [2], used a SensAble Phantom Omni haptic device to generate the position reference signal for an excavator.

Kim, Won Oh et al. in [3] presented a haptic device designed like the shape of an excavator, so the operator can easily understand the motion of the excavator from the haptic device motion.

In the field of wearable devices Kim, Lee, et al. in [4] developed a simple, lightweight teleoperation system for an excavator. Three sensors are attached to the operator's arm, in order to detect his movements. The device is simple, cost effective and lighter compared to typical haptic devices using a force feedback mechanisms. The excavator and robot hand, or arm, can reach the intended positions accurately by using the position feedback. These devices can sense the force feedback and transfer this sensation to the operators by generating repulsive forces at the user interface.

The visual approach can be another interesting alternative in the field of controlling interfaces. Visual interaction offers two advantages over traditional input methods. First, the interface is easy to deploy and can be used anywhere in the field of view of the visual tracker. More significantly, since the mapping from the visual input to action is entirely software based, it is possible to adapt the interpretation to the current task and to the operator in real-time.

Bergh et al. in [5] implemented a real-time hand gesture recognition algorithm based on the inexpensive Kinect sensor. The system is integrated on an interactive robot, allowing real-time hand gesture interaction with the robot. Pointing gestures are translated into goals for the robot, telling him where to go.

Suriyon et al. in [6] proposed to use a QR code as a landmark of a guide route and implement the navigation system that can perform the autonomous run throughout the guide route by using real-time QR code recognition.

Peppoloni and Di Fava in [9] developed an integrated robotic system capable of learning and executing manipulation tasks from a single human user's demonstration. The performances of the system have been verified through a series of tests run on the Kuka youBot platform and all the tools and algorithms are integrated into Willow Garage "Robotic Operating System" (ROS) [8].

III. Novel Human-Machine Interface

In our study we focused on new solutions for human-machine interaction that apply to heavy working machines, with specific care to remotely operated demolition machines. In particular our investigation involved the arm control phases. However this paper will focus only into the latter with the intention of obtaining a set of specification for the usage of this new approaches on a real working machine.

The main goal for a new human-robot interface design is to reduce the interaction effort without diminishing task performance. During the design phase we tried to optimize the overall performance through four metrics (inspired by Olsen and Goodrich in [17]):

1. **Task effectiveness**: How well a human-robot team accomplishes a task, we used a space/time metrics for the assessment;
2. **Neglect Tolerance**: Measures the autonomy of a robot with respect to the task, allowing the user to manage multiple operations;
3. **Interaction Effort**: How complicated is to operate the robot. It involves subtask selection, context acquisition, solution planning and the expression of robot directives;
4. **Usability**: How the user will approach the HMI. It involves the learning curve, the physical and mental load, the user acceptability and satisfaction and the relevance of the robot action in front of the human command.

The operating machine has been provided with an intelligent computing node, enabling it to perceive information through its sensors and a wireless link governed by the remote operator.

A laser/vision system is introduced as interface between the human and the machine. The visual sensing ability enables the machine to perceive environment information (colors and geometry) as well as user commands. The user shows commands to the machine through a set of icons which are moved in the common/shared environment. The machine recognizes the icons' shapes and positions and translates these information in appropriate planning commands.

The use of a laser based projection device will allow the user to control more information simultaneously (e.g. target position and the type of action) in a way that is perceivable by both the user and the machine and robust to acoustic and electromagnetic interferences (as common in industrial environments). In our demos, the operator uses this signal to instruct the machine on the location it has to move to. The machine acquires these iconic information in its field of view and re-maps these absolute positioning information in its relative reference frame. The process is completely transparent to the operator who does not require training to be fully operative.

In our preliminary experiments we use a projector, in place of a simple laser pointer to test how rich can be the set of command data the user can share with the machine. For instance, using multiple markers, the user may issue the machine with complex and landmark based navigation paths.

Two interactive solution have been analyzed.

A. Basic setup

Both solutions refer to the same setup that mimics demolition activities of a working machine. The setup includes a demolition operation and a navigation task within an unstructured environment.

The hardware setup is shown in figure 2. This hardware includes a platform composed by a 3D vision and scan system, and a robotic arm both placed on a mobile olonomous base and served through a notebook, a portable projector, and a small computing device serves as user interface.

During the arm control phases, the control paradigm assumes that the user traces a target destination or a waypoint trajectory (Figure 6) on a wall which is simultaneously visible by the user and the working machine. The vision system recognizes the visual input and sends the trajectory data to the arm control system that closes the working loop executing a trajectory control on the path provided.

Figure 2. Overall architecture of the human-machine interface used during the experimental tests. By following the arrow path, the first two components are worn by the user and controlled to send visual commands to the remote platform; the last three components are placed on the mobile platform and are used to recognize the commands issued by the user. Available visual commands belongs to a set of semantic markers that embed in their shape action related information.

B. Test reference set-up

In a way similar to vision control, a test session based on teleoperated haptic control has been implemented to assess the performance of the novel HMI. Notwithstanding the availability of bi-lateral control techniques [10], so far, in order to experiment the easiness of use of the system we only implemented unilateral teleoperation schemas. The setup is composed by a haptic interface controlling the robotic arm with the objective to trace a defined trajectory over a wall. Figure 4 shows the workflow of this configuration.

Figure 4. Unilateral teleoperation workflow: the three degrees of freedom of the robotic arm are mapped to the haptic device position. A moving reference strategy is implemented to allow the user to move the robotic-arm only when he pushes a button on the handle. The orientation can be changed only between moving phases using a second button on the handle.

IV. Hardware and Software Specification

We have used the KUKA youBot arm [7]as a test platform for our concept design development. The device is composed by: a serial 5DOF robotic arm (655mm height, 0.513 m^3 work envelope, 6kg weight, 0.5kg payload, 0.1 mm repeatability), with a detachable two fingers gripper at the flange. Both devices are controlled by an onboard PC through a share EtherCAT (R) bus.

The software developed makes use the open-source Robot Operating System (ROS [8]) developed by Willow Garage. ROS provides libraries and tools to help software developers create robot applications. It provides hardware abstraction, device drivers, libraries, visualizers, message-passing, package management, and more. We have used open library source code to manage our devices.

The projector device used is the Showwx+ hdmi pico projector made by Microvision. It was chosen mainly for his portability. The Showwx+ is self-powered, has a weight of 0.1 Kg and a size of 1x6x12 cm. It uses a laser technology that allows the projection to be always on focus independently from the distance from the projection surface and without the need of an autofocus device controller. This allows the user more freedom of movement without controlling the image focus. The projector was connected to an Android smartphone (Samsung Note II) to create a simple, lightweight portable device for guidance purposes. The vision was provided by one Microsoft Kinect (R). The device features an RGB camera, a depth sensor and multi-array microphone, which provide full-body 3D motion capture, facial recognition and voice recognition capabilities.

The vision system was integrated in the hardware by developing a specific OpenNI bridge for the proposed architecture (http://www.openni.org/openni-sdk/). We have used a Novint Falcon Hatpic-Device to have a position control of the robotic arm. As for the Kinect we recompiled Falcon compliant USB drivers in a ROS stack to allow our control system to interact with the haptic handle in three dimensions. The Falcon's stack keeps track of where the grip is moved and creates virtual forces to facilitate the user perception of his starting command position.

V. Performance Assessment

This section introduces the setup of different test sessions to assess the performance (according to section III definition) of the proposed human-machine-interface (HMI) in order to obtain technical specifications for future development of the system on a real wotking machine. For such a purpose some preliminary tests were performed involving 6 users (aged 25-40, males). In order to avoid effects of a-priori expertise, all the testers were completely new to the interface operation. Each user repeated each test 3 times. The tests were intended to assess the dexterity of usage of the machine, the overall time spent to accomplish the tasks and the precisions of the operations. Being all the users novices, this tests gives an hint on the usability of the tested HMI and its user-friendliness.

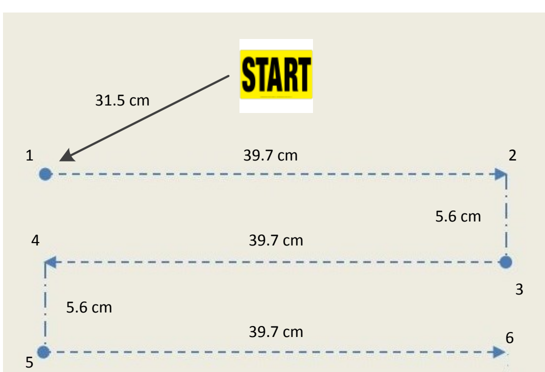

Figure 3. Arm control path with waypoints used in the test sessions.

In this test the user is supposed to drive the arm along a typical path used in demolition scenarios (as shown in Figure 3) when the tool is a demolition hammer. The user will highlight relevant path points by projecting markers on them on the target wall (as shown in Figure 1) so that the robot vision system can recognize them. The Robot localizes the markers using a specific kinect stacks that wraps the ARToolkit in ROS. [11]. The stack improves marker localization using point cloud data from the Kinect. The localized coordinates are processed by the inverse kinematic ROS stack to translate the position acquired in the user space into the coordinate frame used for the arm motion.

This test involved three separate testing sessions. Each session makes use of a different interface to control the robotic arm and they are referred as:

1. **Unilateral Teleoperation**: In this session the user operates by means of an haptic interface teleoperating the robotic arm. This kind of operation lets the user to have direct position control on the end-effector avoiding the need to operate each robot joints sequentially. This lowers the completion time performance with respect to usually employed decoupled joystick or leverages systems.
2. **Projector Operation**: In this session the novel HMI solution is used. The user operates projecting recognizable markers on the trajectory waypoints locations. As soon as the user signals a new waypoint as input to the system, the system acquires the information by means of the vision module and fires the actuators to reach the target position.
3. **Path Operation**: In this session the user operates in a similar way as in the previous session with the difference that the system waits for the user to issue all the waypoints belonging to the desired path. After the user has finished to signals the waypoints, the system processes all the control commands and executes each waypoint reaching control in a sequence.

VI. Performance Analysis

The analysis presented in this section takes into account the four metrics presented in chapter III. Each HMI solution has been evaluated based on the following terms:

- **Task effectiveness** takes into account the accuracy and the completion time of a task for a novel user;
- **Neglect time** represents the time spent by the user to make the robot execute the task in front of the overall completion time;
- **Interaction Effort** and **Usability** have been obtained from a questionnaire filled by users.

To evaluate the interaction effort and the usability we prepared a questionnaire where the user had to evaluate the following point with a value between 0 (feature not satisfied) to 5 (full satisfaction).

Interaction effort:

- Expression of robot directives (transparency between user action and robot execution);
- Mental and physical load (How much challenging is the HMI usage).

Usability:

- Time to learn (How much time a user needs to get confidence with the HMI);
- Task Mastery (If the user feels able to complete a task);
- Easy to remember (if the user needs to get confidence again with the HMI after some time of no interaction with it);
- Pleasant to use (if the user feels the HMI comfortable).

The last part of the questionnaire was left to the user comments.

The performance relative to task effectiveness is presented graphically for each session by a box-plot depicting the smallest observation (sample minimum), the lower quartile, the median, the upper quartile, and the largest observation (sample maximum).

Figure 4 shows the results of the completion time in the unilateral teleoperation testing session. The values here represent the time needed to reach a waypoint starting from the previous one or from the resting position in the case of the first waypoint. The results reflect a good usability for users that approach this kind of teleoperation for the first time. After a short time (few seconds), needed to take confidence with the device, the users are able to perform the task. The main difficulty for the users is to be quite accurate especially in the proximity of a waypoint (Figure 5). The interaction effort focuses on the capacity of the user to translate his/her will through the haptic device.

Moving to the projector operation session, the user feels more confidence with the new system from the very beginning. There is no complex human reasoning to translate the will to move the arm to a definite point in space, just the ability to move the user arm to select the robot arm position goal. The task effectiveness of the moving action is completely determined by the internal algorithm and does not depend on the user skills.

As we can see from Figure 6 the time performance of the operation with the new interface are halved. In this case the operation time refers to the time spent by the robot to reach the waypoint including the time spent by the user to highlight the waypoint. Speaking about accuracy the new user interface can immediately translate the human will into actions resulting in a positioning in space that is more accurate (Figure 7). The error between the coordinate pointed by the user and the position reached by the arm end-effector are just some millimeters due to the arm joints compliance so that we can correctly assume that the accuracy results are valid.

Comparing this results with the previously obtained results we find that using a haptic interface for teleoperation without a previous training makes the accurate positioning a hard task for the user. Moreover the problem of obtaining an accurate positioning affects the task completion time.

Moving to the path operation session, we can see from Figure 8 that the time to reach the first waypoint is greater than the following ones. This delay in fact corresponds to the pointing phase where the user selects, before the automatic execution of the first waypoint reaching movement by the robot, the entire path to be scheduled. As expected the following automatic subtasks are much faster w.r.t. the other non-autonomous operations; this is given by the ability of the robot algorithm to solve its internal inverse kinematics. Figure 9 reports the accuracy of positioning during this testing session and the results improves compared to the other testing sessions. Furthermore it is important to notice that the user interaction time is concentrated at the beginning where he has to teach to the robot the path to accomplish.

Figure 10 presents a global time comparison between the three types of operation. Here the completion time is not referred to each segment of the path but is summed up. The unilateral teleoperation scored the worst result in terms of time of execution. Comparing the projector operation with the path operation we can see that the last one is slightly slower but still comparable. This loss of performance in terms of time of execution is compensated in terms of the freedom of the user after he has completed the waypoints signaling to the vision system. In fact, after the initial pointing operation, he is able to perform other tasks during the machine working cycle.

Figure 11 compares the three HMI solution over a unique scale for the four metrics of performance. The task effectiveness and neglect time refer to the test acquisitions, usability and interaction effort refer to the user feedback after the test execution. The evaluation is made just to compare the three operation modalities. We used the scale of values between 0 and 5 of the qualitative questionnaire even to evaluate task effectiveness and neglect time features. Although the monolateral teleoperation has quite good performance, the other two solutions show more convincing features. Even though the projection and path operation have similar performances we can evince some interesting characteristic from the user feedback. The projector operation presents the best usability, in fact the user feels really comfortable controlling, in real time, the end effector and feels the full control of the machine. On the contrary, the interaction effort results more complex due to the need for the continuous correction of the trajectory to maintain the position accuracy. Conversely, the path operation shows a better interaction effort due to the lower working time needed by the operator and the absence of path correction by the user. This is paid in terms of usability, in fact the user reports the lack of the possibility to correct the end-effector trajectory during the machine working cycle. There isn't a best configuration between these two but they complement each other depending on what kind of operation has to be made. The path operation is suitable for less risky and accurate tasks, not having the real time control of the machine and leaving the user some free time to spend in other task. The projector operation is suitable for more complex tasks where the user has to be present during the whole operation or a preventive trajectory cannot be foreseen.

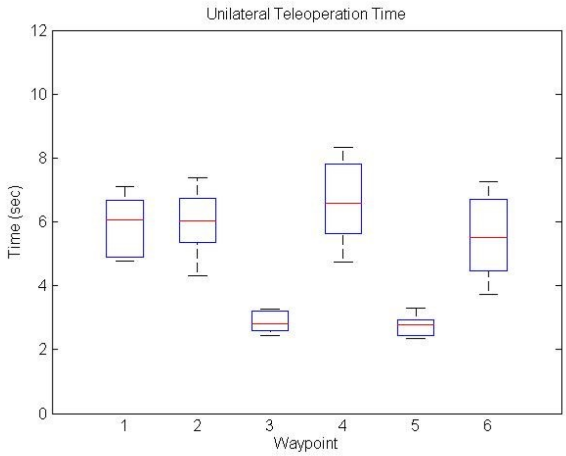

Figure 4. Box-plot of the elapsed time to reach the next waypoint in the case of unilateral teleoperation.

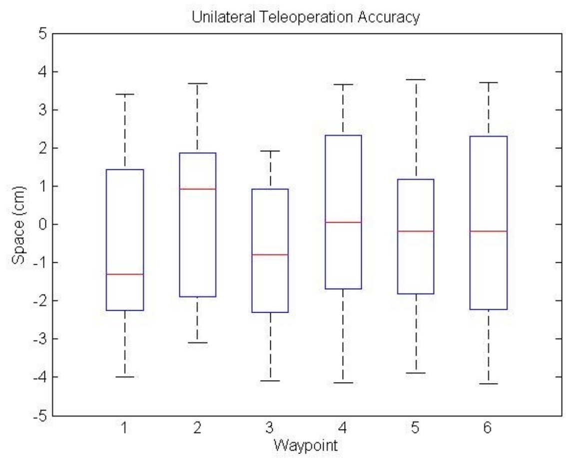

Figure 5. Box-plot of the position accuracy on each waypoint location in the case of unilateral teleoperation.

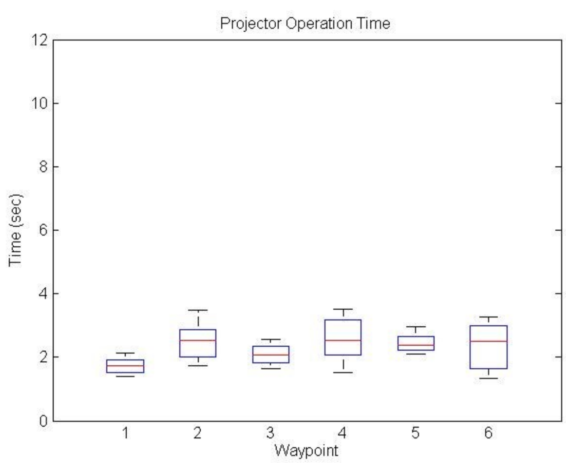

Figure 6. Box-plot of the elapsed time to reach the next waypoint in the case of the projector operation.

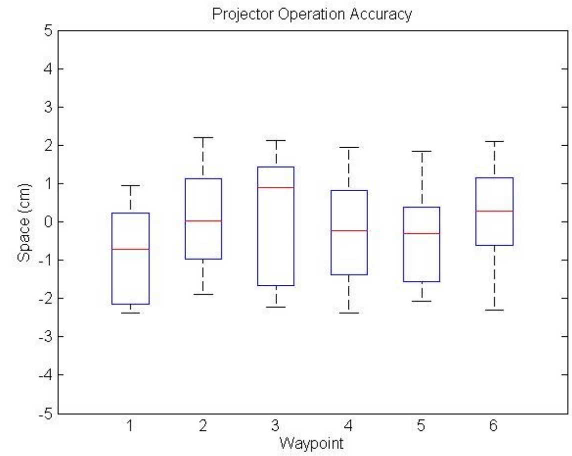

Figure 7. Box-plot of the position accuracy on each waypoint location in the case of projector operation.

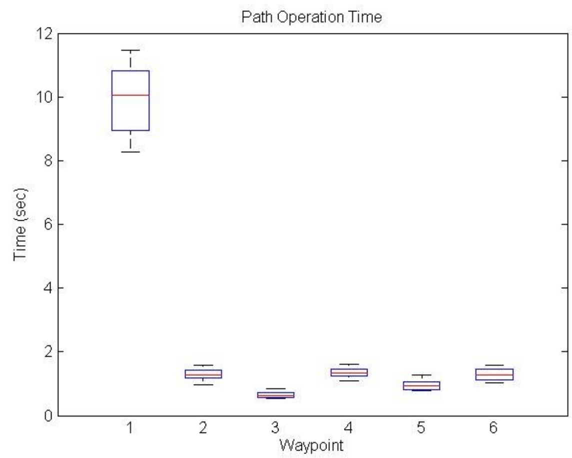

Figure 8. Box-plot of the elapsed time to reach the next waypoint in the case of path operation.

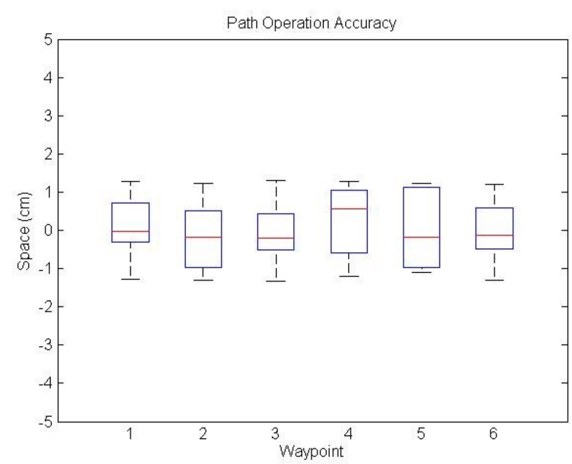

Figure 9. Box-plot of the position accuracy on each waypoint location in the case of path operation.

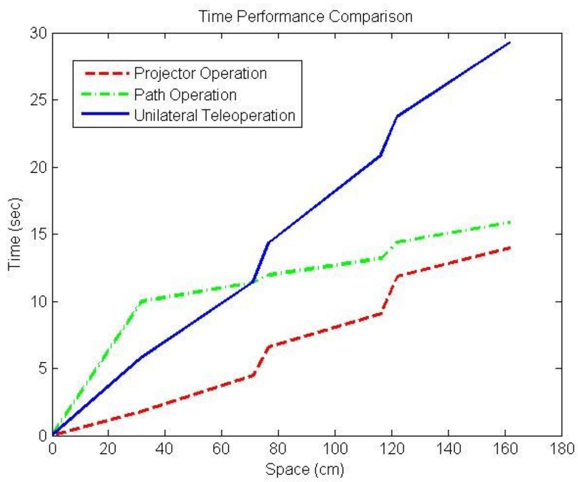

Figure 10. Performance comparison of the different arm control techniques.

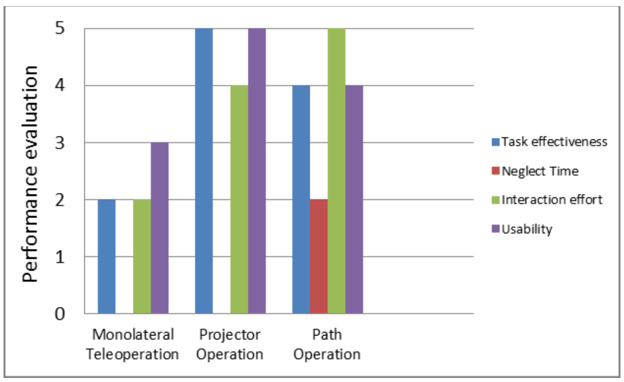

Figure 11. Qualitative performance comparison of the Human-Machine Interface solutions. The values of evaluation go between 0 (feature not satisfied) to 5 (full satisfaction).

VII. CONCLUSIONS AND FUTURE WORK

This paper presented a new kind of Human Machine Interface for working machine operation. A preliminary setup has been designed and tested in various operation modes with the aim of obtaining the specification for a future system integrated on a real working machine. Tests results have shown a good performance in terms of tasks completion time and accuracy. In particular the new approach results very attractive for novel users and allows to accomplish other activities during the automatic execution of the operations. In the future the new HMI will be applied to a real demolition vehicle and more tests with an improved hardware set-up will be carried out.

ACKNOWLEDGMENT

We would like to thanks YANMAR R&D Europe (YRE) for sponsoring the presented research.

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