Designing Interactive Robotic Games based on Mixed Reality Technology

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***Abstract*—This paper focuses on an emerging research area represented by robotic gaming and aims to explore the design space of interactive games that combine commercial-off-the-shelf robots and mixed reality. To this purpose, a software platform is developed which allows players to interact with both physical elements and virtual content projected on the ground. A game is then created to show designers how to maximize opportunities offered by such a technology and to build playful experiences.**

I. Introduction

Robots are getting ever more commonplace in our lives. Service robots, in particular, represent today a key market for consumer electronics (CE), with an ever growing number of robotic systems being exploited in everyday activities. Besides smart vacuum cleaners, connected lawn movers, photography drones and many other serious robotic applications, an area that is worth attention in the CE perspective is represented by *robotic gaming*. Drone races and battles have now thousands of fans and are broadcasted worldwide, but there is also a number of vendors that commercialize an incredible variety of tiny toy robots, each with its own set of games.

Although the increasing adoption of Artificial Intelligence (AI) techniques will make these systems ever more smart and flexible, so far the most common use of the above robots is teleoperation. Roughly independently of the robot's aspect and capabilities, human players are expected to drive them on the ground, in the air or under the water using their personal devices or a dedicate controller. Games generally consist in making the robot complete a particular task (possibly before other players do) or defeat another robot in a given contest; other games may require the player to collaborate with the robot or get advice from it while solving a challenge (e.g., when the robot acts as a facilitator or a referee).

The limited usage scenarios envisaged for these products could make players soon lose their interest. Moreover, with the exception of a few examples, human-robot interaction paradigms used so far are poorly natural, and this fact could make players even less engaged in the gaming experience.

However, there are two trends that promise to revolution the above scenario. The first trend is represented by a new paradigm for robotic gaming known as Physically Interactive RoboGames (PIRGs) [1]. The basic idea in PIRGs is to make the robot become a peer to human players, by endowing it with rational, autonomous behaviors. The second trend has been introduced in [2], and goes under the name of "phygital play". The core concept is that a *contamination* of physical and digital elements in games could contribute at increasing the level of entertainment, by bringing gaming back to its primordial roots and fostering healthy and social behaviors (e.g., by reducing time players spend in front of a screen).

In the last few years, principles underlying the above trends have been exploited to develop several games [3–4], in some cases also studying (and confirming) the added value deriving from their combination [5–10]. In particular, one of the ways that has been explored to realize the envisaged contamination is by immersing existing robots in an Mixed Reality (MR) environment created by "augmenting" the physical world with digital content displayed using floor projection. It is worth observing that, with this approach, it is possible to give CE robots originally meant for a specific application a "new life". Moreover, applications envisaged for this technology do not necessarily have to be focused on entertainment: in fact, there are examples of such games used for education, training, rehabilitation, etc.

By building upon results reported in the literature, with this paper we aim to share the preliminary outcomes of a study which we are carrying out to define the principles that need to be considered in creating these MR-based robotic games. In doing that, we also addressed one of the main issues of PIRGs, which consists in making robots appear as rational, autonomous agents even when they are not provided with capabilities suited to this purpose. In particular, we focused on robot's localization and we showed how, by exploiting Augmented Reality (AR) and combining it with another CE product – precisely, a Virtual Reality (VR) kit with headset, controllers and sensors – a home setting can be quickly turned into a projection-based robotic gaming environment.

II. Related Work

Early examples of robotic games can be dated back to the 90's, when robots were experimented as players' opponents in static games, like chess [11]. In the years that followed, robots gained an increasingly larger set of capabilities, which allowed them to be employed in much more dynamic gaming scenarios, requiring ever higher levels of autonomy [12].

In the frame of robotic gaming, PIRGs are games in which autonomous agents (either digital or physical, including at least one robot and one human player) interact in a possibly unpredictable environment according to determined rules, with the ultimate goal of letting players have fun. In [1], several guidelines have been set for suggesting game designers how to create effective PIRGs. These guidelines invite designers to a) *consider environment's characteristics and agents' capabilities* in order to define meaningful roles and goals in the game; b) *define a story* for the game and stick to it (like in any game); c) *reduce, reuse and recycle* (R^3) existing software and hardware components, with the objective to keep down costs; d) foster *safety* and *simplicity*,

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especially when targeting young players; e) make the robot appear as a *rational agent*, meaning that expedients need to be used to ensure that players consider it as a peer (thus, if the robot does not possess, e.g., the ability to see because it comes without a camera but vision is required to make it behave autonomously, then an external system shall be used to make players perceive it as provided with that capability); (f) *exploit senses*, to attract players' attention on the robot and make the gaming experience more engaging.

Several PIRGs have already been proposed following these guidelines. For instance, work in [1] shows a game in which the player has to fight a flying drone with a lightsaber. In [3], the "Statues" game is created using a wheeled robot endowed with a laser range sensor. In [4], a toy robot is provided with autonomous navigation skills and acts as a referee to check player's actions in a room-scale card-sorting game.

As said, when the concept of PIRGs blends with that of phygital play, richer gaming scenarios can be created in which physical, robotic elements are enriched with digital, virtual content (and vice versa). An early example of MR-based robotic game is shown in [5], where a projector is used to create virtual paths, obstacles and battles on the ground for both robots and players. Another example is reported in [6]; here, half of the gaming area is displayed on the screen using VR, whereas the other half is represented by a floor projection on which robots and human players are allowed to interact. In [7], an affordable, extensible platform leveraging projected fiducial markers and mobile robots for the creation of active learning environments is presented. In [8], a collaborative roleplay game is shown, in which a toy robot is programmed to follow projected lines and respond to players' interactions based on proximity beacons.

III. Challenges in Robotic Gaming

Although a number of MR-based robotic games have been created, there are several problems that might prevent their effectiveness (and, as stated in [1], require to follow an agile development process and to continuously test choices made). One of these problems is indeed robot's localization, an essential feature to allow developers create games with autonomous agents – especially when commercial-off-the-shelf (COTS) robots are used to comply with the PIRG's R^3 principle. The second problem pertains game design: in fact, the phygital play perspective adds further constraints on top of PIRG's principles, that can hardly be addressed by simply adopting a trial-and-error development process. In this paper we specifically tackle these two problems, by presenting a new projection-based platform for MR-enabled robotic gaming (extending that in [9]) which leverages mass-market VR technology to implement robot tracking, and by showing how to build a game compliant with PIRG guidelines on it.

A. Robot Localization in a Projected Game

The platform in [9] was designed to support a number of players and (different) robots and, in principle, different ways to precisely determine their position in the gaming area.

Concerning players, it was demonstrated that their position (and body movements) could be tracked rather well using established technology (like RGB-D cameras or wearable sensors). The same cannot be said, regrettably, for the robots. In fact, it frequently happens that, on the one hand, sensors available onboard (cameras, wheel encoders, IMUs, etc.) are not sufficient to let them localize themselves with the needed accuracy. On the other hand, when external tracking systems are used, important assumptions have to be made, e.g., on the aspect or motion of the robots. The above limitations can only be partially addressed by using, e.g., sensor fusion techniques capable to integrate both robots' endogenous and exogenous localization information [10].

Taking into account the above considerations, we started to create a new platform that leverages a COTS technology to track robots in a room-scale gaming environment without relying on their onboard sensors as well as by limiting as much as possible the constraints on their physical aspect. In particular, the Lighthouse technology developed by Valve – the same used in the HTC Vive VR headset – was selected.

Lighthouse is a laser-based positional tracking system that uses several so-called "base stations" (emitters) to determine the 6DOF position and orientation of tracked elements (receivers) in their combined field of view (FOV). Generally, two base stations are used to cope with occlusions. Tracked objects can be either the hand controllers of an immersive VR system or any other physical element equipped with the receiving technology (which is made available, e.g., by HTC through the Vive Trackers). With the only requirement for the robot being the ability to carry on one of the above accessories and keeping it in the FOV of the base stations, this technology can ensure a tracking accuracy of 1–2 cm with a precision of 1–2 mm and a latency of about 20ms.

A. Design of Projection-based PIRGs

Once a suitable technology for tracking the robot (so that platform knows its location and can drive it as needed), for a phygital game with robots to be successful (hopefully, more than without the robot) it is essential to focus design efforts on the actual motivation for having the robot in the game.

Basically, compared to a traditional or digital game (e.g., leveraging only the floor projection or a totally virtual environment) a MR-based PIRG has to boost the physicality of the experience. That is, the robot needs to *play a central role in the game*, independent of the actual goals set for it. This aspect is partially related to the PIRGs' principle that suggests to exploit the senses of the players. Indeed, the use of effective visual and sound effects can help keeping the players engaged. However, based on our experience and on the analysis of games developed so far, it is much a matter of making the robot frequently *announce its presence*, e.g., by challenging the player and communicating or interacting with him or her. The above requirement has also to do with another principle of game design which calls for *believability*. In fact, the robot may lose players' attention simply because it does not move or behave in a plausible way: for instance, using a robotic ball like Sphero to create a game in which the robotic agent needs to move over straight lines will definitely end up with a poorly engaging experience since the robot would only be able – by design – to move over swaying paths.

Another aspect to be taken into account is the *dynamism of the experience*, since game theory suggests that this factor is directly related to engagement. Dynamism can be pursued in many ways. For the games that can be implemented with the devised platform, dynamism can come from projected content and from robot's and players' motion. Thus, while designing the game, a tradeoff needs to be found among the above aspects, by considering, among others, the size of the gaming area, the speed of the robot, the number of players, etc.

This aspect is closely related to other well-known design principles that concern the need to *pursue and achieve goals* as well as *consistency* and *fairness*. Shortly: a robot which plays the role of the opponent and is slower than the players would probably set challenges which are not particularly engaging for the players; however, a robot that is too fast would make it impossible for the players to reach their goals, and would make them perceive the game as unfair.

Another PIRG guideline which is worth to be recalled for MR-based robotic games concerns safety: a highly interactive (e.g., high speed) game would probably raise engagement, but would also lead to possibly hazardous situations.

Lastly, *collaboration* is a factor that is often considered in a positive way by game designers: however, in a robotic game leveraging room-scale floor projection, having too many players sharing the gaming space with a moving robot could seriously lead to hazardous behaviors.

IV. SYSTEM DESIGN

As said, by taking into account the cues in the previous section, we started the development of a robotic platform that integrates the HTC Vive tracking technology and enables MR-based games including autonomous robots. Platform's architecture is depicted in Fig. 1 (projection logic is omitted). Sources are available for download at https://goo.gl/rQfUYv.

Robot tracking data are obtained by a Vive Tracker mounted on the robot itself and are sent to the gaming platform using the SteamVR SDK. The platform includes a game logic component (implemented in Unity), which is responsible for creating the digital content to be projected and to drive the robot based on the current game conditions.

In order to foster a strong interaction (also physical) between the robot and the human players, it was regarded as particularly important to let the players share the gaming area with the robot. To this aim, it was necessary to track also the players. Since the Lighthouse's emitters can be used to track multiple objects, it was decided to add further receivers on the players (for ergonomics reasons, the Vive controllers were used, which are basically Trackers with handles). By letting the players move in the environment and occlude (be occluded by) the robot, we were able to test the behavior of the tracking system under stressful conditions.

In order to support fairness, several sub-goals (or sub-tasks) had to be defined for the game, to be fulfilled in sequence (thus preventing players' from moving too fast). Moreover, in order to avoid potentially risky situations, the robot was provided with the ability to sense human players' position w.r.t. it and to stop when they get too close.

Finally, visual and audio feedbacks had to be used to inform the player on game's state. Besides changing colors and shapes of content displayed on the floor and associating

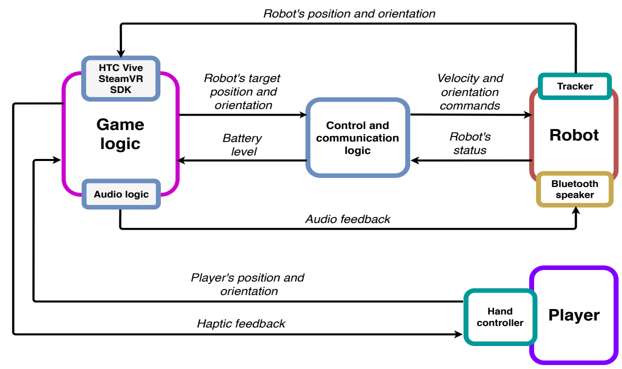

Fig. 1. Architecture of the (projected) MR-based robotic gaming platform.

sound effects to relevant events, in order to make the robot assume an even more central role in the game it was chosen to let it become a further sound source. Thus, by mounting a Bluetooth speaker on it, the robot could be used to play sounds capable to attract players' attention (e.g., to inform them about where it is, that it is approaching, etc.).

V. GAME DESIGN

Many reasons discussed in the previous sections suggest to balance the choice of the robot with the design of the game. Thus, it is convenient to start the game design by choosing the robot based on hints in Section IV and then tailor the game to it. The robot chosen is the Parrot's Jumping Sumo.

A. Robot Characterization

Several empirical tests were performed to determine the optimal operating conditions for the robot and, hence, the requirements for the game (e.g., taking into account level of dynamism, believability, etc.). Test were carried out by using the Parrot's app and making the robot follow pre-defined, closed paths by changing its speeds and well paths' length and shape. It was observed that, when set to move at the maximum speed of 2 m/s, the robot was not able to stop where indicated due to overshooting. Moreover, it was mostly unable to move in a linear way; rather, it generally exhibited swaying movements, especially after sharp turns between waypoints. Measured drifts between the first and last waypoint were in the range 20–50 cm. When setting a lower speed, e.g., of 1 ms/s, a more linear movement was obtained, with drifts in the range of 5–10 cm. It is worth saying that tests were not meant to extensively assess robot's behavior under any possible operating condition, since this is not what it would be expected by/requested to a game developer. Notwithstanding, interesting cues for game design were obtained. In fact, we observed that in order to make the robot move very fast, poorly accurate positioning and movements had to be accepted. Moreover, additional space had to be allocated around the gaming area to manage overshooting and avoid collisions with walls and other elements. Thus, game dynamism had to traded off for robot's control. The above considerations made us opt for a robot's speed of 1 m/s.

Robot control relies on the availability in the game logic of a virtual replica of the physical robot. By defining the target position and orientation for the virtual robot, the control logic sends appropriate commands to control the physical robot's motors. Control logic was split in two components: one is responsible for managing robot's orientation with respect to the target, the other is in charge of controlling distance to it. Each component implements a PID controller. The PID on distance receives in input integer values in the 0–100 range (not directly correlated to speed), whereas the PID acting on orientation receives values corresponding to relative angles. The above components can be used either in sequence or in parallel: the first approach would reduce the swaying effect, as position would be controlled only once orientation has been adjusted; the second approach would be faster, as position and orientation would be tuned at the same time.

B. Game Design

Considering the 3×2 m area available for the projection in our lab (roughly matching the area that can be tracked by the emitters), we chose to limit the number of players to one.

In the devised story, player's role is that of a stationmaster who is in charge to control a number of railway switches to make sure that trains reach the correct stations. In the game there is a single train, represented by the robot. The train moves (autonomously) over the railways, which are split in cells. Cells can represent signals, switches and stations. The train stops at signals and follows switches' direction (Fig. 2).

The player can change the state of signals and switches by positioning himself or herself on the corresponding cell and standing still for few seconds. While moving in the gaming area, he or she continuously occludes projected content: notwithstanding, being the robot a physical entity, the player is always able to spot it. In response to player's interaction, signals disappear, whereas switches change their direction to that of player's body. When the game starts, a number of signals is randomly distributed on the tracks. Switches are given a random direction, whereas one of the stations is selected as the first trains' destination (and it starts blinking).

The train starts moving towards that station. The player has to change the state of signals and switches as needed. If the train reaches the right station, the player earns lives; if it reaches the wrong ones, the player loses lives (or points).

The game projects a circular red shape on the player's feet, which identifies a sort of "safety area": if the robot reaches it, it stops for a while (to avoid collisions), but the player loses a life. Lives are projected on the floor. The game ends when the player succeeds in making the train reach all the stations (thus winning the game) or when he or she loses all the lives. A video with gameplay is available https://goo.gl/6uV115.

As said, though the game never stops, a reasonable balance between the speed of the various elements was achieved by articulating the story in sub-goals, represented by the set of stations to be reached by the train: this choice requests the player to perform quick actions, which nevertheless are followed by periods in which the robot is given time to complete the assigned task.

Furthermore, the player is requested to keep the focus on the robot, since he or she needs to study its motion w.r.t. the tracks while maintaining a sufficient distance from it. Lastly, the speaker onboard the robot plays a sound that resembles that of a real train, making the player aware of robot's position and distance at any time.

Fig. 2. Picture taken during gameplay in the projected environment.

VI. CONCLUSIONS AND FUTURE WORK

Work reported shall be regarded as a preliminary attempt to describe principles to be taken into account when creating phygital, MR-based robotic games, since other variables shall be considered to cover the whole design space. Moreover, a rigorous evaluation has to be carried out, e.g., by continuing works in progress [13], in order to quantitatively assess the impact of suggested practices in different application fields.

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