Robot Gardens: An Augmented Reality Prototype for Plant-Robot Biohybrid Systems

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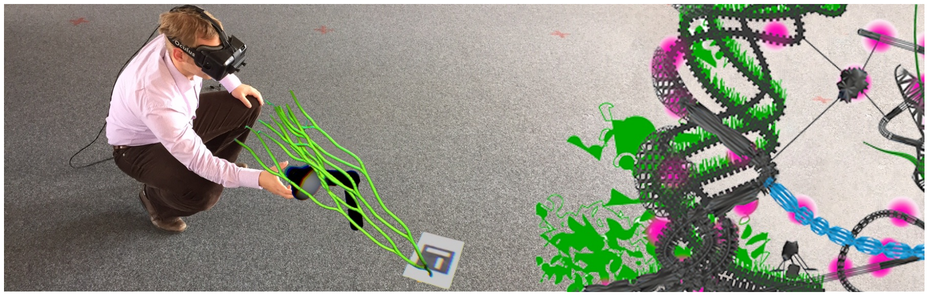

Figure 1: *Photomontage of the "Robot Gardens" Biohybrid AR Prototype.*

Abstract

Robot Gardens are an augmented reality concept allowing a human user to design a biohybrid, plant-robot system. Plants growing from deliberately placed seeds are directed by robotic units that the user can position, configure and activate. For example, the robotic units may serve as physical shields or frames but they may also guide the plants' growth through emission of light. The biohybrid system evolves over time to redefine architectural spaces. This gives rise to the particular challenge of designing a biohybrid system before its actual implementation and potentially long before its developmental processes unfold. Here, an augmented reality interface featuring according simulation models of plants and robotic units allows one to explore the design space a priori. In this work, we present our first functional augmented reality prototype to design biohybrid systems. We provide details about its workings and elaborate on first empirical studies on its usability.

Keywords: augmented reality; interactive simulation; biohybrids

Concepts: •**Applied computing** → **Computer-aided design;** •**Human-centered computing** → *Usability testing; Walkthrough evaluations; Mixed / augmented reality;*

1 Introduction

flora robotica is a research project that aims at the exploration of the interactions between robots and plants, or biohybrid systems. In particular, it sheds light on possibilities on the instruction and guidance of plant growth and dynamics. The applications of biohybrid systems have numerous ramifications into art, design, architecture and construction. The resultant biohybrid artefacts are tailored towards individual spaces and needs. They are adaptive in terms of changing environments and utilisation behaviours, or aesthetic appreciation. Based on appropriate computational models of robots and plants, we can simulate and predict how biohybrid systems unfold over long periods of time. In this work, we present an augmented reality (AR) concept that projects a corresponding realtime-capable biohybrid system simulation into real-world spaces. Our hardware setup is comprised of an Oculus DK2 head-mounted display in combination with a stereoscopic OVRvision camera and a gamepad to realise precise input commands. The resultant *Robot Gardens* AR system empowers its users to grow plants and influence their developmental patterns by means of simple, placable, configurable robotic units. We show the functionality of the Robot Gardens AR system by means of a first usability study. The remainder of this paper is structured as follows. In Section 2, we present the *flora robotica* project in more depth. Here, we especially stress the envisioned collaborative interaction facilities. As Robot Gardens requires the user to manage and concert numerous interwoven robotic and biological entities, we also reference seminal works in human-swarm interaction. In Section 3, we detail the Robot Gardens AR concept, including not only the relationships of the hardware-setup but especially the realised user interface and its implications for perceiving and shaping the AR. The evaluation in Section 4 is three-fold, cumulating results from a usability inspection, usability tests and interviews. We conclude with a brief outlook on potential future works.

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2 Related Work

In this section, we provide more details on the application domain of our AR concept for designing and exploring biohybrid systems. In its second part, we elaborate on approaches of human-swarm interfaces that make large numbers of entities malleable by human users.

2.1 *flora robotica*

The *flora robotica* project [Hamann et al. 2015] investigates the possibilities of biohybrid systems in which plants and robots collaborate and live together in symbiotic relationships. The primarily targeted outcome of these systems are architectural artefacts. Biohybrid systems are designed, for example, to grow into living structures such as benches, walls and roofs. In this process, the robotic components guide the plants' growth in terms of primary attributes such as direction and branching, or secondary attributes such as structural resilience and longevity. The robots achieve these results for instance by exploiting the plants' phototropism—shining light towards or shielding light from the plants. Alternative direct means of robotic influence can be physical barriers and supporting elements as well as the provision of water and nutrients. For example, a robotic structure can be a set of rods and nodes forming a scaffolding with simple electronics attached. At later stages of their growth, plants could, in turn, support the robotic components by supporting their weight or by pushing them towards the sunlight to feed their solar cells and recharge their power. The interplay between plants and robots is artistically illustrated on the right-hand side in Figure 1; scaffolds (in grey and blue) serve as frameworks for plants to grow on (shown in green), embedded robotic units sense the environment and emit signals (both shown as pink spheres) to guide the plants' growth and determine the configuration of the scaffolds. A key characteristic of a biohybrid system is its long life-cycle—potentially decades—which motivates comprehensive in-silico planning, before actually deploying it. Targeting spatial artefacts, this especially motivates devising an AR interface to experience the evolution of a biohybrid system in specific environments. Due to their complexity and dimensions, collaborative interfaces could further the application of biohybrids. An according approach, *Social Garden* was also proposed in [Hamann et al. 2015]. Here, a digital component serves as a searchable database of several (physical) *flora robotica* sites that are connected online. In this way, the exchange and continued development of user generated designs will be promoted.

2.2 Human-Swarm Interaction for Biohybrids

Biohybrid systems can be understood as swarms due to their large number of participants with individually limited capabilities in sensing, computing and acting. For simplicity, in Robot Gardens, we consider two homogenous swarms, one for robots and one for plants. For example, consider a system with two lamps, elevated from the ground and at a certain distance from each other. Consider further a single plant growing from the ground, centred between the lamps. Turning one light off would cause the plant to move towards the only active light source. When controlling a swarm of robots a user can neither control nor observe each robot individually. Next to best practice guidelines for human-computer interaction design [Foley et al. 1984], the following desirable features of human-swarm interfaces have been identified [Bashyal and Venayagamoorthy 2008]. They need to promote desirable emergence, facilitate local rather than global interaction, allow to scale the swarms' dimensions, provide interfaces for human collaborators, and to enable to interact with subsets of swarm individuals. In [Bashyal and Venayagamoorthy 2008], the authors also showed that a human can support the swarm to boost its task-specific performance. In the given experiment, a user took control of a single individual of a swarm of robots. Human intelligence and background knowledge about building spaces allowed the user to help the swarm to fulfil its goal and find a radiation source faster. The interface of another swarm of robots established communication with a user wirelessly (to receive commands) and via audio (to signal their correct functionality) and light signals (to indicate its internal state). The wireless signal was aggregated and sent to the user or disseminated across the swarm by a gateway robot [McLurkin et al. 2006]. In the context of biohybrid systems, such an interface could well be used to signal required interferences by the human user, for instance the need to adding another robotic rod to a scaffolding system. At the same time, it could communicate the concise location of attachment without the need for rigorous structural analyses and omitting the (wireless) communication overhead. In [Daily et al. 2003], an AR concept was presented for guiding a swarm of search and rescue robots through an unknown building. Here, the robots would enter a building, search for human presence and, if successful, send out navigation instructions to a rescue unit waiting outside on stand-by. As the robots do not know their exact position, they would align in a chain pointing towards an identified victim and propagate their local position data through the chain by means of infrared signals. The user, wearing a head mounted see-through display with a camera attached, would perceive the decoded spatial information as an arrow pointing in the proper direction. An overview of the current state of the art in human-swarm interaction can be found in [Kolling et al. 2016].

3 Robot Gardens

The Robot Gardens AR system combines a simulation of basic plant growth, simplistic robotic entities with an AR interface. The latter features a head-mounted display, a stereoscopic camera and a gamepad for user control. A QR-code serves as the origin of a global coordinate frame for the augmented simulation space, and heads-up displays (HUDs) provide the user with the required configuration data of plants and robots. In this section, we detail the main components of the Robot Gardens AR concept and explain their interplay.

The utilised plant model relies on swarm grammars (SGs) [von Mammen and Jacob 2009], an agent-based extension to L-Systems [Prusinkiewicz and Lindenmayer 1996]. A basic SG consist of two parts: (1) A swarm of agents of various types that concert their movement similar to boid swarms [Reynolds 1987], and (2) a set of production rules that determine the agents' construction behaviours as well as their reproduction (branching of the plant) and differentiation.

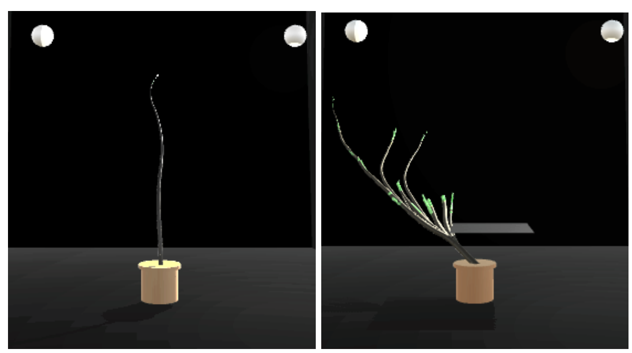

Figure 2: *Left: Many times over, a plant grows towards the one activated light source. Right: A plant avoids shadow.*

We further adjusted the SG plant agents to follow light sources [Ahmad 1999] and to avoid shadows [Sauer et al. 2008] (Figure 2). Parameters such as branching behaviour, lignification or growth

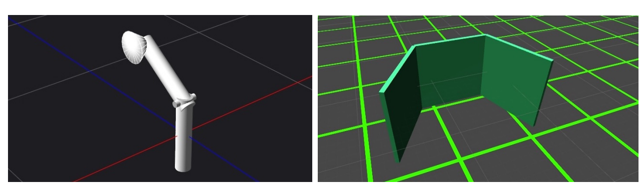

Figure 3: *Left: A "light-bot". Right: Three wall units forming a room-divider.*

rate can be adjusted to approximate the behaviours of different real plants. For our prototype, it was especially important that the plant model allows for realtime interaction as the designer might want to explore the arising growth dynamics under various conditions. First investigations on biohybrid systems only consider very simplistic robotic units. Accordingly, our first AR prototype only features lamps that can be place, rotated, scaled, switched on and off and configured in terms of light intensity and simple physical obstacles such as walls and poles (Figure 3).

Ideally, the user should be able to interact and configure technical components of the system by means of hand gestures as suggested in Figure 1. The user should further be empowered to explore larger areas occupied by biohybrid systems and be able to reconfigure them or re-consider his previous design decisions. As hinted at above, the AR component of our concept implementation funnels a stereoscopic video stream to a head-mounted display, identifies the location of a QR-marker and projects virtual information on top of the live view. Head-tracking allows the user to assume different viewing perspectives, a gamepad gives him the opportunity to configure the biohybrid model and to navigate the simulation. In particular, the user can seed new plants, place and configure robotic units, and play and pause the simulation.

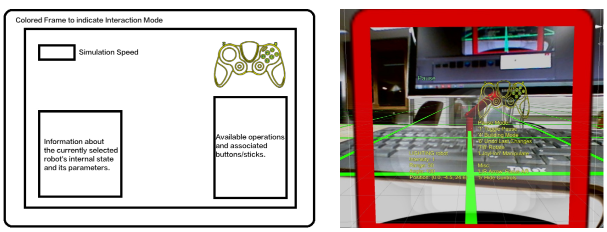

Figure 4: *Left: GUI schematic of the HUD. Right: The augmented rendering.*

Figure 4 shows the HUD layout and an actual rendering. During our tests, we quickly found that the most crucial information we need to convey to the user is whether the simulation is running or whether he can plant seeds and configure robots. We decided to colour the frame of the view either green or red, respectively, in order to provide a mode indicator that proves effective, independent of the user's gaze. While pausing the simulation, the user may select individual robots by looking at them. The selected element is highlighted to establish the link to the displayed information. The commands to configure the selected robot are shown in pause mode as well. We would have preferred working with a gesture-based interface only, e.g. using the LeapMotion device [Weichert et al. 2013], but in our early tests, the reliability of the gamepad improved the usability enormously. By pressing buttons on the gamepad, the user can, for instance, rotate or scale a robot, increase and decrease the intensity of its emitted light. When pausing the simulation, the simulation state is saved to allow the user to leap back in time, reconfigure the system and explore different outcomes. When playing the simulation, the user may adjust the speed of the simulation.

4 Preliminary Usability Tests

Our current prototype serves two purposes: (1) To communicate the concept of an AR solution for biohybrid design challenges, and (2) to channel our next efforts towards advancement of biohybrid explorative design solutions. In order to address the latter, we first inspected the prototype's usability and, second, we tested it with several users of different, non-computer science backgrounds [Preim and Dachselt 2015]. As we did not provide extensive introductory materials, provided a personal introduction to the prototype's goals and interface. Personal assistance was also needed to remind the test persons of the interplay of gaze-based selection, i.e. focusing the view centre on an object, and gamepad-based configurations. In addition to UI-specific hurdles, the system suffered marginal stability issues due to driver conflicts.We introduced a tiled floor to compensate for the lack of spatial cues caused by uniform, directed lighting of the augmented graphics assets.

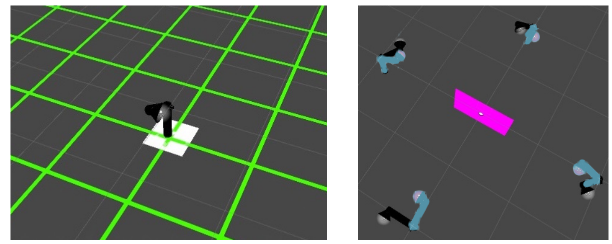

Figure 5: *Task A: Place a lamp-bot in the white square. Task B: Re-orientate the lamp-bots to match the cyan projections.*

We tested the usability of the Robot Gardens AR concept empirically with the help of 12 participants. All of them were students at the age between 22 and 25 years. One of them was a computer science student, another one had experience in game design. The remaining ten test persons had no background in computer science. The experiments were setup as follows. First, the testers were personally introduced to the interaction modalities. We explained the general AR setup, the modes of interaction, element selection based on head orientation as well as the gamepad layout. Next, the testers were briefed on three specific tasks (A, B and C), one at a time. For better discernibility on paper, Figure 5 only shows the experiment setups that augmented the lab space during the tests. Tasks A and B had to be performed three times in order to quantitatively capture any learning effects. Task A was designed to familiarise the user with the user interaction setup. Here, he was asked to place a lamp-bot within a specified area. In task B the user learned to configure the bots. Here, he was surrounded by four lamp-bots that he had to re-orientate to have their arms point towards himself (the pink rectangle represents the position of the user). Finally, the user was tasked to grow a plant around a pole by freely placing and configuring lamp-bots. In order to complete task A, the users had to focus on the target area and press a specific button on the gamepad. All users were able to complete task A right away and they showed significant improvements after each trial, as reflected by the successive averages (20.48s, 11.12s, 8.42s), variances (85.69, 55.07, 10.81) and standard deviations (9.26, 7.42, 3.29). In order to complete task B, the users had to select each of the lamp-bots and rotate them into the right direction. Again, the users performed task B three times, whereas a significant improvement could only be determined after the first trial, with a steep drop of the average time needed from 41.76s to 22.27s (20.57s on average for the third trial). We assume that the initial familiarisation combined with the acquired skills from task A resulted in the huge performance leap and its sudden stagnation.

Task C requires the user to proactively utilise the acquired skills to design a first biohybrid artefact. In particular, the task was to make a pre-configured plant (featuring a single agent) grow around a pole at least twice by strategically configuring and activating an arbitrary number of lamp-bots. Figure 6 shows the plant being guided around the pole in a sequence of screenshots. During the experiments, the users deployed between one to fourteen lamp-bots. Figure 7 shows two solutions users designed in AR. Before and after the usability experiments we asked the users about their background and their experience, respectively. Focusing on the input modality, we asked

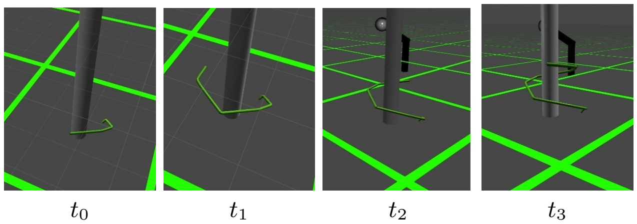

Figure 6: *The plant is guided around the pole utilising only one lamp-bot following a stop-motion strategy that constantly switches between the configuration of the lamp-bot and the simulation of plant growth.*

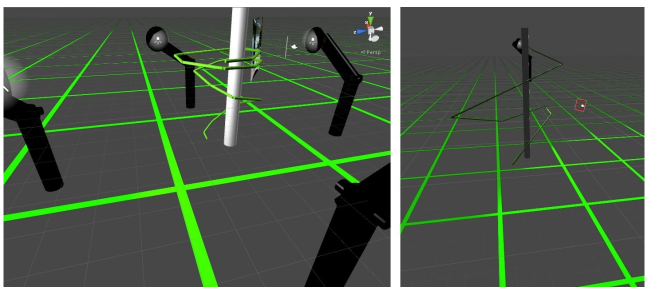

Figure 7: *Left: Four lamp-bots take turns in guiding a plant around a pole. Right: One lamp-bot is re-configured several times to guide the plant development.*

whether they owned a gamepad (7 out of 12) and to rate their experience with its usage (75% of the gamepad owners considered themselves proficient in its use). After the AR trials, the users were asked about possible improvements to the prototype. In unison, the users complained about the tethered hardware setup which bound them to rather small areas. Some users also mentioned that they would have liked to have a visual representation for the areas of influence for light robots, and objects to turn slightly opaque when hiding others. To improve immersion and also interaction accuracy, one test person suggested to let the user yield shadows on the simulated elements based on general lighting information and the implicitly tracked body posture. The grid on the ground as well as the use of head orientation for target selection were positively recognised.

5 Summary & Future Work

The Robot Gardens AR prototype allows to configure robots and see how they impact the development of plants. The models underlying robots and plants are rather modest but they are realtime-capable and extensible. In order to master the challenge of explorative generative design, the user can navigate the simulation, instantiate, introspect and configure the simulated elements. Usability inspection confirmed the usefulness of personal instructions and the limitations of the hardware setup. Usability tests and interviews were conducted based on three experiments that introduced the basic interactions to create and configure a biohybrid system. The experiments and subsequent interviews confirmed the effectivity of the prototype but also unearthed some weaknesses such as tethered hardware as well as the poor integration of rendered objects into the real world. Next to improving these aspects, we believe that the prototype would greatly benefit from switching to a more robust, more mature platform (such as the HTC Vive) as it would not only provide a better tracking and rendering infrastructure but also because of its advanced input controllers. They would not only facilitate faster and more complex introspections and (re-)configurations of simulated elements but they would also empower the user to concert larger numbers of simulated agents in line with human-swarm interactions. We are convinced this will make a huge difference when promoting the exploration of biohybrid design spaces by artists and architects alike.

Acknowledgements

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