Diver-based Control of a Tethered Unmanned Underwater Vehicle

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Abstract: Human-robot communication with an underwater vehicle is a complex problem. Standard wireless communication protocols are unavailable, and the lack of direct supervision from surface-based operators reduces situational awareness and operational efficiencies. Here we describe recent research results with tethered operation of autonomous vehicles at depth by diving operators. We review different operational designs and describe a novel system based on exploiting advances in lightweight computational platforms (tablet devices) as the basis of the operator control console. Recent field experiments are also described.

1 INTRODUCTION

Effective human-robot communication is essential everywhere, and nowhere is that more the case than when communicating with robots that operate underwater. The underwater environment places limits on communication infrastructure and at the same time the dangerous nature of the environment means that even simple errors in autonomous operation can lead to the complete loss of the vehicle. Given this, the development of effective communication strategies for unmanned underwater vehicles (UUVs) is critical. Unfortunately not only does the underwater environment require effective communication between a robot and its operator(s), it also places substantive constraints on the ways in which this communication can take place. The water column restricts many common communication approaches and even systems that might be appropriate for underwater use such as ultrasound tend to have low bandwidth and high power consumption. As a consequence the physical tether has emerged as a common communication conduit for human-robot communication underwater.

The most common way of structuring human-robot communication for autonomous underwater vehicles is from a surface controller via a physical tether to an underwater vessel that is not directly visible to the operator (see (Nokin, 1994), (Lee et al., 2000), (Aoki et al., 1997) and Figure 1). While such an approach can provide for excellent communication between the operator and the device as well as providing a conduit for power and vehicle recovery if necessary, a tether, and in particular a surface-based tether also presents several problems. The operator is typically located in some safe, dry location (as shown in Figure 1(a)). The operator has no direct view of the autonomous vehicle. Furthermore it is typically the case that the operator's only "view" of the operational environment is via sensors mounted on-board the platform. As a consequence the operator tends to have very poor situational awareness.

The actual UUV operator is, of course, not the only human involved in controlling an underwater vehicle. Although a tether provides a number of advantages, at the end of the day it is a tether that must be properly managed. Different deployments necessitate different tether strategies but personnel must be deployed in order to deal with the tether. Figure 1(b) illustrates the complexity of this problem for the shore deployment of an underwater sensor package. A number of personnel are engaged in the task and the ability of the various personnel to communicate among each other effectively is key to successful UUV deployment.

The vast majority of UUVs operate on their own. In contrast, the AQUA platform (Dudek et al., 2005) (see Figure 2) is a UUV that is designed to operate with humans in close proximity. This property generates a number of interesting constraints and opportunities with respect to operating the robot with a tether. In order to ensure that the robot operates safely in the presence of other humans (divers) in the environment it is desirable to place the human operator underwater, rather than on the surface as depicted in Figure 1. When operated in this configuration the operator has an enhanced view of the work-site as well as any other

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(a) (b)

Figure 1: The realities of surface-based tethering. Here surface-based operators (a) communicate with a submerged device (b) through a tether. Note that the operators do not have direct view of the device, nor can they see any divers who might be accompanying the device at depth. For this deployment also observe the large number of cable handlers required to service the cable as it travels through the surf zone.

Figure 2: KROY, one of the members of the AQUA family of robots operating at depth. KROY is a swimming hexapod. Each of the six fins can be controlled independently.

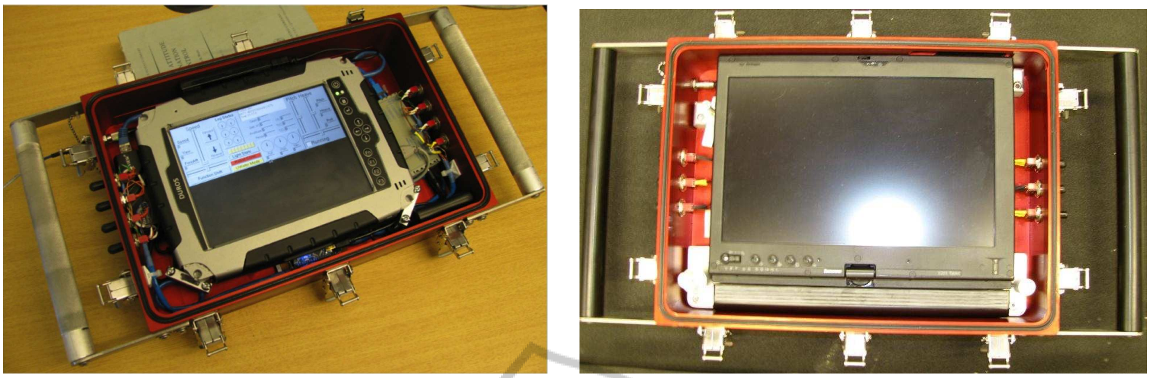
divers in the vicinity. Furthermore, it is possible to position tether wranglers at depth and for the operator to have a line of sight with the various personnel involved in the deployment.

Although this operational mode can provide a substantive enhancement to the operator's ability to control the vehicle and generally enhance the situational awareness of the operator, it is now necessary to construct an operator interface that can function at depth. The classic keyboard, computer and mouse found in Figure 1(a) is neither waterproof nor capable of withstanding the pressures encountered within the diver-operator's operational range.

The problem of migrating a UUV operator's interface to an underwater platform was considered in (Verzijlenberg and Jenkin, 2010). In this work standard tablet PC's were mounted within water tight and pressure resistant housings (see Figure 3). The surface-based user interface was adapted to take input commands from a collection of buttons mounted on the sides of the housing (see Figure 3) but besides this the basic GUI was left unchanged. Power for the other components contained in the housing were either provided by drawing power through the USB-ports of the laptop or through small USB-batteries that provide 5V. The devices were designed to have approximately 60 minutes of operation once sealed, a time that was consistent with the operational regime of the robot once deployed. The housings were augmented through the addition of an IMU that allowed the entire tablet to be treated as an underwater joystick and the operator could command the pitch/yaw/roll of the vehicle through the orientation of the tablet relative to gravity.

In total three different generations of these tablets were constructed (the second and third generation versions are shown in Figure 3). Tests with the AQUATablet were very successful (see (Verzijlenberg and Jenkin, 2010) and (Speers et al., 2011) for details) but a number of issues were identified when operating the robot at depth.

- The form factor of the PC requires that the housing be relatively large. Although the waterproof container can be machined to be relatively light when empty, it is critical that this container be (approximately) neutrally buoyant when deployed underwater. (If it is not neutrally buoyant then the diver-operator will have to compensate for this when operating the device). In order for the entire tablet to be neutrally buoyant it must weigh the same as the weight of the water it displaces. Thus the relatively large volume of the tablet housings requires that the tablets be weighted through the



(a) 2nd generation. (b) 3rd generation.

Figure 3: PC tablet-based AQUATablets. These two versions of the AQUATablet are based around tablet PC's. The PC provides computing and network support. A collection of water-proof switches on the sides of the housing provide basic input. A GUI provides visual output to the user. Housed within the tablets are an Arduino that interfaces with the switches and an IMU that allows the entire tablet to be treated like a joystick. When operating at depth a clear plastic cover is secured over the front of the display. The robot is tethered via a fiber optic tether. A transducer between the PC's Ethernet port and the optical fiber connection is also housed within the case.

addition of external mass. This makes traveling with the tablets before deployment more difficult, but it also means that the tablets have a large moment of inertia. They may be "weight-less" underwater, but they are still difficult to move. This makes using the entire tablet as a joystick more difficult.

- The tablet housings have a reasonably large surface area. This means that when operated in a strong current or swell the tablet case acts as a drag or sail on the operator.
- The use of a tablet PC increases the cost of the components inside the waterproof housing. The unfortunate reality of underwater robotics projects is that there is always the potential for water to penetrate the housing with disastrous results for the electronics (especially in salt water). One reason for the increased cost associated with PC-based electronics is that the process of monitoring the physical switches and the IMU requires special purpose electronics that are not normally found on tablet PC's.

When work began on the original AQUATablet there were very few options in terms of obtaining the necessary computational power in a tablet-like form factor. Recent advances in tablet technology now make the necessary display, connectivity, and computational power readily available in a lightweight, small form factor package. Here we describe an updated version of the AQUATablet based around an Android-based ASUS Nexus 7 tablet. In addition to providing the necessary control inputs to communicate with the UUV, the Nexus 7 includes WiFi, GPS and accelerometer sensors which reduces substantively the cost of the components and the size of the revised "lightweight" AQUATablet.

2 A LIGHTWEIGHT AQUATABLET

The lightweight AQUATablet is shown in Figure 5. As with the earlier designs of the AQUATablet the housing is essentially a waterproof box designed to withstand the pressures associated with an operator-diver operating the vehicle at 100'. (Note that the robot can descend below the diver, but that given the limits associated with diving on air, 100' is a reasonable constraint on the anticipated maximum depth for the operator tablet.) Whereas the housings for the AquaTablet 2 and 3 shown in Figure 3 were milled from aluminum, it was possible to mill the lightweight AQUATablet from Plexiglas given its smaller dimensions.

As with the earlier models the AQUATablet is equipped with a small number of switches (now two) with which the user can interact with the housing. (As the tablet is operated inside a sealed housing it is not possible to interact with the tablet through its surface, as would normally be the case.) The housing itself contains the following:

- An ASUS Nexus 7 which is self contained for power, and which provides display, computation and a number of sensors and communications options (including WiFi). The Nexus 7's only physical connection is a USB port.

- The USB on the Nexus 7 is connected (via a small powered USB hub) to a Phidgets interface board which provides connectivity to the external switches, and an Ethernet adaptor that connects to the external fiber connection to the robot.
- A small battery pack provides power to the USB hub and network hardware.

2.1 Software Infrastructure

Earlier versions of the AQUATablet utilized a modified version of the GUI software used by a standard PC when controlling the UUV. The decision to move to an Android-based tablet necessitated a change in the underlying software infrastructure.

The AQUA robot platforms wrap the underlying Robodevel infrastructure within a network of Robot Operating System (ROS) (Quigley et al., 2009) nodes. Within ROS overall robot control is modeled as a collection of asynchronous processes that communicate by message passing. Although a very limited level of support does exist for ROS on the Android platform, it is not a fully supported environment for ROS. In order to avoid any potential inconsistencies between the Android-ROS implementation and supported ROS environments, it was decided to not build the software structures on the Android platform in ROS directly, but rather to exploit the `rosbridge` (Brown University, 2013) mechanism instead. `rosbridge` provides a mechanism within which ROS messages are exposed to an external agent and within which an external agent can inject ROS messages into the ROS environment. This injection process uses the `WebSocket` (Hickson, 2010) protocol which means that provided the external agent has network access to the ROS environment it can be physically located anywhere.

Within ROS messages are passed using an internal protocol. The `rosbridge` framework communicates these messages to and from the external world in the form of `yaml` (Yet Another Markup Language) strings. Such yaml strings can be used directly by an external agent but perhaps the most convenient way is to use `json` (Corckford, 2006) to map yaml strings to instances of objects in the environment of the external agent. This approach has a number of advantages in terms of interfacing a lightweight device such as an Android tablet to a robot running ROS. First, standard libraries exist that support the `WebSocket` protocol on the Android device (e.g., (Tavendo, 2013)) and native support for `json` exists for many platforms including the Android.

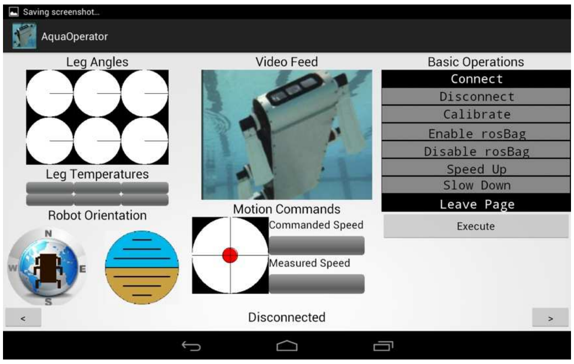


Figure 4: The lightweight AquaTablet user display. The user interacts with the device through tilting the device and also through two two-way switches mounted on the side of the housing. Pitch and roll of the device are used to control the pitch and heading of the robot. See text for details.

2.2 User Interface

One issue with the development of user interfaces to be operated underwater is the limited options for human-machine interaction. Standard devices such as keyboards, mice and touch screen surfaces are not practical underwater. For example, even though the touch sensitive surface of devices such as the Nexus 7 and the iPad can be waterproofed the pressure of the water column causes the entire surface to register a touch event at relatively shallow depths. As a consequence most interactions are limited to waterproof switches and sliders that expose some physical component to the external environment and then transfer the event in to the pressurized housing. A wide range of physical interaction devices exist – often developed for the underwater camera housing market – as well as standard electrical switches which was the design decision made here.

The decision to limit the number of input switches was made both from practical constraints as well as experience with the previous AquaTablets. The reduced physical size of the lightweight AquaTablet reduces the potential locations for switch placement. Furthermore, each switch increases the potential for water penetration of the housing. Beyond these physical constraints, experiments conducted with previous AquaTablets (which had as many as eight two-position switches) demonstrated that the cognitive loading associated with operating a vehicle was not well served by providing the operator with a multitude of input switches. It was just too easy for an operator-diver to forget the intent of the various switches, and that diving gloves made it easy for divers to press multiple switches.

Located on the side of the tablet housing are two

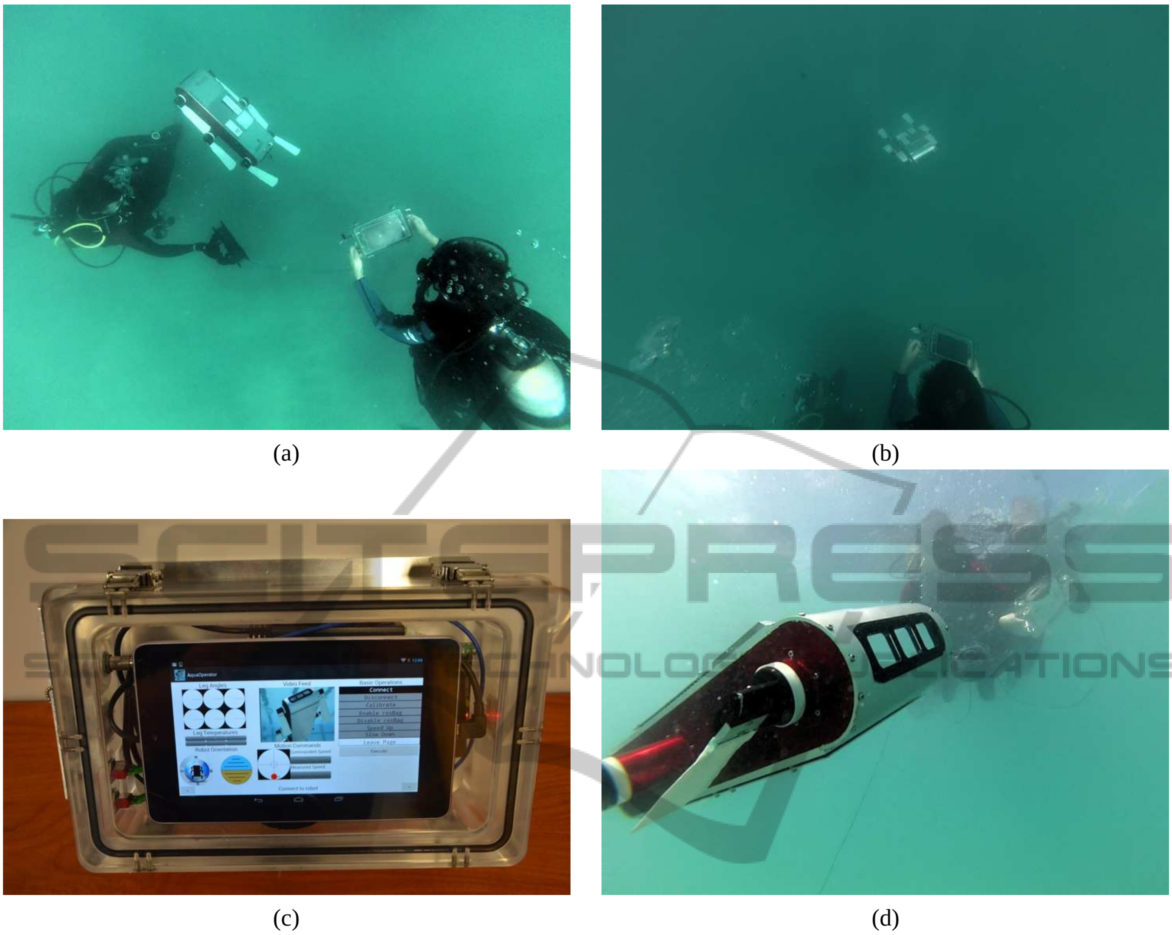


Figure 5: The lightweight computer-based underwater tablet. By utilizing a smaller footprint device it is possible to reduce substantively the mass/volume of the operator console. (a), (b) and (d) show an underwater operator teleoperating the vehicle. As can be seen the device is now sufficiently small and lightweight that it can be easily carried by the diver. The device itself (shown in (c)) is essentially an Android tablet (the ASUS Nexus 7) with external devices to connect to switches on the outside of the housing and to the optical fiber tether that connects to the robot.

two-way switches. This provides the potential for four "button press" like events. Lightweight devices such as the Android have user interfaces that are intended for much more sophisticated inputs (e.g., multiple touches over their display surface) and thus it was necessary to construct an input strategy that was appropriate for the limited set of input events available.

The primary user display is shown in Figure 4. The display is broken down into three columns. The left most column shows instantaneous leg angles and leg temperatures providing a snapshot of the current state of the low level systems on the vehicle. Below this the current heading and pose of the vehicle are displayed via a compass and an artificial horizon.

The center panel shows a live video feed from the robot (in Figure 4 the live video feed is simulated by a static image), followed by the current commanded speed of the vehicle and the orientation of tablet housing relative to gravity (indicated by the red circle in the center of the display). Experiments with the previous AquaTablets demonstrated that it is very easy for a diver to make incorrect judgments of the true vertical given the lack of obvious landmarks to vertical underwater. (See (Jenkin et al., 2009) for details on quantifying a diver's ability to perceive the vertical when suspended in water.) Housing tilt is yoked to changes in intended vehicle depth while housing roll is yoked to changes in intended vehicle yaw.

The right panel shows a set of potential inputs. Given the switch-based input paradigm it is not possible for the operator to just "choose" an input by pressing on it. Rather the operator cycles through the various active buttons using one of the switches while one of the positions of the second switch causes the current button to be executed.

The lightweight AquaTablet is shown in operation in Figure 5. Figures 5(a) and (b) provide a sense of scale of the tablet in operation and the reduced size/weight of the tablet relative to the earlier tablet designs is clear. The reduced mass/volume of the tablet in particular makes the device much easier to deploy and use than the previous versions of the device.

Figure 5(c) shows the Nexus 7 mounted inside the housing with all of the associated cables, connectors and power supply. The entire device is not that much wider and taller than the Nexus itself as can be seen, although it is about 2” deep. In order to make the entire device more easily operated by a diver the housing is attached to a base that is slightly larger than the housing. This provides a shield for the switches to reduce the possibility that they might be flicked accidentally and a mounting point for a safety line so that the housing is not lost if it is dropped by a diver.

3 EXPERIMENTAL VALIDATION

The lightweight AquaTablet has undergone extensive sea trials off the coast of Holetown, Barbados. When controlled by the tablet the robot is normally operated by a three person team. A cable wrangler deals with spooling and unspooling cable to the robot, an operator controls the tablet and a third team member acts as a safety diver/videographer.

The reduced volume/mass/surface area of the tablet relative to the earlier versions of the device was found to be of particular benefit. As can be seen from Figure 5 the form factor of the lightweight AquaTablet makes operation very straightforward. The device can be held quite easily by a diver operator without interfering with the diver’s ability to maintain their position/orientation within the water column and indeed to swim near the robot when it is operating.

Having a direct line of sight to the vehicle makes it substantively easier to operate than when operated from above the surface. The choice of a limited number of input switches was also found to be effective as this reduced the potential for the diver operator to have to “hunt” for the right input. The reduced visibility available underwater – including fogging of the operator’s goggles – means that it is difficult to label the various switches in a meaningful way and the reduced number of switches actually reduces the potential for confusion.

Although the vehicle state display was useful when initially launching the vehicle it was found that during nominal operation such displays were essentially ignored and that for nominal operation a larger video display feed might be more appropriate.

4 DISCUSSION AND FUTURE WORK

Although the choice of the Nexus 7 as the display-compute unit enabled the construction of a smaller underwater tablet, the decision did have significant implications in terms of hardware and software. It was decided in the project to utilize an “un-rooted” (aka stock) Android tablet. This reduced the options for various pieces of external hardware as they must function “out of the box” with the Android. Of particular importance here is the limited availability of USB-Gigabit Ethernet adapters that are supported on the Android.

From a software point of view the Android platform provides substantively less computing power and memory than the PC-based tablets used previously. As such certain decisions in terms of the software infrastructure had substantive implications in terms of overall system functionality. By default, `rosbridge` will send every message it receives to an external agent. The limited processing power of the Android can make servicing all of these messages problematic. Throttling messages prior to exporting them via `rosbridge` may be appropriate or necessary.

A more subtle issue related to the use of the `rosbridge`-WebSockets-yaml-JSON pipeline is the large number of String objects that are created in the process. Although this is not normally an issue in PC-based implementations, Android processes must operate within a very limited memory footprint. Minimizing the size of the String’s being processed and the number of String objects that are created is important in order to ensure liveliness in terms of the user interface. This problem becomes most acute when images are transferred through yaml. yaml is a printable encoding which means binary data such as images must be encoded as printable characters. This means that the “raw” yaml message is extremely large. This message must then be decoded into an image (another large structure on an Android platform) which must be further drawn onto internal structures within the Android in order to display them. Although it is certainly possible to send an image stream encoded as yaml messages to an Android platform, it is not necessarily the best way given the memory and network bandwidth constraints involved.

The lightweight AquaTablet was designed to be sufficiently small that it can be mounted on top of the robot directly. In this configuration the device can act as an external display for operators swimming near the robot, as well as providing GPS information and WiFi communication when the robot is at the surface. The choice of `rosbridge` as the communication mechanism here allows information to be easily passed from the robot to off-board agents also operating within their own ROS environments.

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REFERENCES

Aoki, T., Maruashima, T., Asao, Y., Nakae, T., and Yamaguchi, M. (1997). Development of high-speed data transmission equipment for the full-depth remotely operated vehicle – KAIKO. In *OCEANS '97*, volume 1, pages 87–92.

Brown University (2013). rosbridge. http://www.rosbridge.org. Accessed February 10, 2013.

Corckford, D. (2006). The application/json media type for JavaScript object notation JSON. Netowrk Working Group RFC 4627.

Dudek, G., Jenkin, M., Prahacs, C., Hogue, A., Sattar, J., German, A., Liu, H., Saunderson, S., Ripsman, A., Sinhon, S., Torres, L., Milios, E., Zhang, P., and Rekleitis, I. (2005). A visually gudied swimming robot. In *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, pages 1749–1754.

Hickson, I. (2010). The WebSocket API. W3C Working Draft 16 August 2010.

Jenkin, H. L., Zacher, J. E., Dyde, R. T., Harris, L. R., and Jenkin, M. (2009). How do SCUBA divers know which way is up? the influence of buoyancy on orientation judgements. *J. of Vision*, 9(716):716a.

Lee, P., Jeon, B., Hong, S., Lim, Y., Lee, C., Park, J., and Lee, C. (2000). System design of an ROV with manipulators and adaptive control if it. In *2000 International Symposium on Underwater Technology*, pages 431–436.

Nokin, M. (1994). ROV 6000 – objectives and description. In *OCEANS '94*, volume 2, pages 505–509.

Quigley, M., Gerkey, B., Conley, K., Faust, J., Foote, T., Leibs, J., Berger, E., Wheeler, R., and Ng, A. Y. (2009). ROS: an open-source robot operating system. In *Proc. Open-Source Software workshop at the International Conference on Robotics and Automation (ICRA)*.

Speers, A., Topol, A., Zacher, J., Codd-Downey, R., Verzijlenberg, B., and Jenkin, M. R. M. (2011). Monitoring Underwater Sensors with an Amphibious Robot. In *Proceedings of 2011 Canadian Conference on Computer and Robot Vision (CRV).*, pages 153–159, St. John's, Nefwoundland.

Tavendo (2013). Autobahn websocket. http://autobahn.ws. Accessed February 10, 2013.

Verzijlenberg, B. and Jenkin, M. (2010). Swimming with robots: human robot commuication at depth. In *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, Taiwan.