Designing for Depth: Underwater Play

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ABSTRACT
The underwater domain is an alluring 'other world', inviting of human-aquatic interactivity and bodily play and yet it is also an extreme environment as it is inhospitable to support human life without external air-supply. Playful interactions are therefore matters of life and death in the underwater domain. We correlated data on human-aquatic interactions and narcosis with a range of game design principals to produce a design pallet for digital underwater play from water level to 30m depth. We also present a proof-of-concept system called Gravity Well as an exemplary research tool. Through our work, we aim to inspire other researchers and designers to consider creating digital play in and under water.

Categories and Subject Descriptors
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design, Human Factors.

Keywords
Diving, Exertion Games, Aquabatics, Underwater robotics

1. INTRODUCTION
Popular aquatic sports from underwater rugby, to hockey and polo have inspired novel types of stunts, games and aquatic play. Our field of inquiry and related research spans the fields of sport, art, entertainment and occupational diving. With our work ‘Designing for Depth’ we aim to explore underwater digital play by appropriating exertion game design thinking towards full-bodied play experience in the aquatic domain. We present an overview of the unique factors influencing such systems including an initial design guide relating to narcosis that illustrates the complexity that is not normally considered in parallel HCI interactions. We also present Gravity Well as an exemplary research tool. Finally, our long-term research goals are presented with the view to support and facilitate the design of engaging experiences across multiple altered-gravity domains.

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2. UNDERWATER PLAY
We begin with the assumption that the aquatic domain is inherently novel but equally hostile. It is a sensory-rich immersive environment that offers opportunities for playful experience and presents unique challenges for designers of interactive systems. According to Schouten et al. interactive playgrounds should meet three conditions to provide a rich game experience: adaptation, personalization and context-awareness [4]. To this we add that any underwater interactive systems should be drown-proof [5]. Designing interactive systems for underwater play therefore requires specific understanding of pressure changes and altered gravity domains for it to become an interactive playground. We see the aquatic domain as a decentralized interactive environment [6] and therefore by creating specific aquatic interactive design elements we believe that underwater play can facilitate player exploration and engaging experience.

Figure 1. Gravity Well: Prototype testing.

2.1 Related work
We investigate elements of aquatic play-objects and playful strategies in prior art. We focus on interactions beyond ‘screen-based’ simulations, and basic ‘water-proofing’ or ‘tethering’ of land or shore-based systems to define the underwater play experience. The *Dolphyn* [7] comprises of an underwater-computerized display system with various sensors and devices conceived for existing swimming pools and shores, associating computer functions, video gaming and multi-sensory simulations. This system enables the participant to experience immersive interactive environments whilst underwater (whether while holding breath, snorkeling or with diving equipment) yet relies on direct communication to a shore-based system. The *Underwitter AR* [8] prototype is a mobile underwater Augmented Reality system comprised of a semi-transparent display in front of a diving mask, a backpack computer to detect underwater markers and video stream from a camera on the top of the diver's mask. The footage and data from inertial and magnetic field tracking of the diver’s orientation generates real-time virtual 3D scenes. This research informed the game development *AREEF* (Augmented Reality for Water-based Entertainment, Education and Fun) [9].

By building upon actual experience, designers can build in important safety references such as the Archimedes Principal and the effects of buoyancy and resistance on movement [10], audio and visual distortion through water, and new wetware input controllers to translate the important 'feelings' of being in an aquatic domain through the animation of human diving [11]. Games like *Virtual Oceanarium* [12] and *Swimitate* also use augmented reality to enhance the experience of underwater play whilst the player slashes around in water. Swimgames show that this kind of interactive technology in public swimming pools can facilitate engaging experiences and promote well-being [13].

Bächlin et al. produced the *SwimMaster* [14] consisting of accelerometers to offer feedback to a swimmer while swimming. Other wearable interfaces such as the *AQUATablet* [15] lean on robot interaction devices designed to be operated by a diver tethered to, or in visual communication with, an underwater robot. The *Buddy Robot Swimoid* [16] support swimmers in three ways: self-awareness, coaching and game. We discover that much of the computer-robot interaction that responds to biological motion underwater is not used to mimic human motion, but to locate it [17].

3. DESIGNING FOR AQUABATICS

We combine our experiences in Aquabatics and exertion games to undertake research of underwater play: Aquabatics connects commercial diving, underwater technology with live art pedagogies to describe human performance underwater [1] and exertion games are digital games controlled by gross-motor movement [2]. We believe it is important to recognize that the domain of underwater play does not meet most standard HCI analytical frameworks and like so many non-conventional exertion games it slipstreams across the territories of games and sport, rehabilitation, diving work, and works of art, dance technology and martial arts [18]. The framework for underwater play is re-conceived through investigations of game-directed exertion [19] only within the location specificities that are unique to the aquatic domain. In the aquatic domain, the body of water, and the body of the participant are perceived as one entity body [20], therefore, the resulting perspectives rely on observation across human-aquatic interactions.

Examples of controlled water environment interactions and tools can be examined in the entertainment arts. Aquatic troupes like The Aquabatics, UK and Cirque du Soleil "O" in Las Vegas [21] are examples of this. We learn from the historic film production *original million-dollar mermaid* starring Annette Kellerman [22] and her mermaid protégée Esther Williams [23] about performing underwater with a camera. We learn of the risks of human-aquatic interaction through the public spectacles of stunt professionals and escapologists [24], most notably illustrated by the works of Harry Houdini [25]. Each of these artists perform their acts in a well-engineered aquatic domain with specific knowledge of the technological and biological conditions for underwater play perfect for inspiring audiences and designers [26].

We next examine the world of the elite breath-hold community, in particular apnea and freediving disciplines and technologies [27]. These practices are frequently described as sport, art and meditation and they provide a way for designers to begin to understand the unique characteristics of human-aquatic interactions [28]. The first author references her own live art aquabatics practice as a point of departure [1]. The experiential and embodied knowledge of performing aquabatics is useful for two reasons. Firstly, it influences design thinking and encourages a departure away from many land-based assumptions to include the specific physiological and psychological impacts of being underwater. In other words, perception of sight and sound varies with depth and therefore impacts the overall experience. Furthermore the underwater experience is perceived through a kinesthetic combination of "somatic movement" and "bodily awareness" [29]. Secondly, it serves as a point of departure to re-examine the perception of experience in the context of the discipline that emerged from dual pro-prioceptive awareness and the inter-dependence on neuron-associative conditioning in occupational diving training and experience [30].

In occupational diving, including commercial diving, scientific diving, the underwater film industry and military-related diving, there is high demand for human awareness and performance capability [31]. The body and mind is exposed to the elements such as cold temperatures and currents, and while operating with other stressors affecting interactions such as narcosis and decompression-related exposure. There is industry demand for interactive technologies that reduce environment stressors on divers, and increase human sensory adaptation and performance particular for tasks that cannot be performed by robots, remotely operated vehicles and autonomous underwater vehicles. We found a general bias towards interactive technologies that are focused on enhancing the diver's ability to "see" as first priority, [32] and then "navigate", "communicate" and "orientate", often through augmenting connectivity with the job site, other divers, robots and the surface crews [33]. The demand for sophisticated photogrammetry for the virtual exploration of underwater archeological sites, for example, creates a demand for underwater heads-up-displays integrated in personal masks and underwater computers [34] and the creation of Google Ocean will aid the focus on data [35]. Proposals and prototypes for novel Underwater Augmented Reality Systems (UWAR) have been many and varied, however most seek a robust solution to increase a commercial diver's capacity to detect, perceive, and understand elements in underwater environment operations [36].

To date, this challenge is being explored through a range of augmented "visual" technologies [37]. The risk and limitation of this is that visual augmentation, particularly at close-range, adds to the diver's visual workload and can become an unsafe distraction or hindrance. Furthermore, the system must be robust so as not to confuse the diver with conflicting or contrary visual data to process [38]. For this reason, combinations of systems approaches including less attention-demanding vibrotactile [39] and audio interactions are also explored in underwater space operations and in rehabilitation systems designed for vision impaired and less-able-bodied divers [40]. Similar applications are utilized by space professionals for use in space [41] and in training and simulation in space analogue environments [43] including underwater in neutral buoyancy training facilities and ZeroG to prepare for microgravity [44].

3.1 Designing as a matter of life and death

There is a multiple of critical life and death considerations for achieving 'drown-proof' design in the aquatic domain with site-specific equipment including advanced life support technologies such as SCUBA, in addition to human and technology exposure to the liquid-environment, and the body-shocks to pressure-variation.

In preparing definitions and design guidelines within the aquatic domain with the intent to design unique exertion games that facilitate full-bodied play experiences we looked at the issue of Narcosis as one example of a complexity that is not normally considered in parallel land-based exertion games or HCI design. Partial pressures of gases (N, O) absorbed become toxic to the

NARCOSIS	ABOVE/0-30m BELOW	EXPLANATION	NOTES FOR DESIGNERS	*GRAVITY WELL*
MOOD	Nominal state/feeling	Narcosis produces a narcotic-like effect.	Design to harness mild euphoria mood – but not to distract from water safety.	Sci-Fi futuristic theme adding to euphoric feeling.
	UW Mild euphoria			
INTELLECTUAL FUNCTION	Open to ideas/rational	See above. Eventually leads to hallucinations, stupor death >90m.	Clear, concise simple tasks OR open play design. Rules aid concentration at depth. Tasks assist direct focus.	Low-level intellectual function required for play. Open to interpretation. User determining rules.
	UW Fixed ideas & mild reasoning impediment			
AUDITORY & VISUAL STIMULI	See color spectrum & hear direction of sound	See above. Lens of eye must adapt. Vestibular disturbance too. Vibrations reach the ear simultaneously.	Sound travels 5x faster in water than air. Sound attenuates less UW. Most sound is reflected at surface. Water absorbs visible spectrum.	Vibrant LED color tones easily detected underwater. Low-intensity LED array shows movement. Ambient sound.
	UW Delayed response, omnidirectional sound, loss of visual spectrum			
BALANCE & COORDINATION	Stable axis. Fixed gravity reference	Pressure effects vestibular function & nervous system. Buoyancy affects all aspects of balance and coordination.	Water creates drag and resistance. Design to harness both the abilities and challenges to the body and the properties of movement due to buoyancy.	The overt design feature. A user-designed interaction sensing aquabatic motion (body & body of water)*. Physically altered buoyancy, balance and coordination.
	UW Little impediment, slowed movement, altered-buoyancy			

Table 1. Signs and symptoms of Narcosis 0-30m underwater compared to land. Our additions in the form of implications for game designers are on the right.

human body when breathing air underwater. This effect, known as Narcosis, is experienced as a narcotic impairment to which there is no human tolerance and may be fatal or hazardous [45].

Training cannot be assumed of the player, therefore these factors can become hazardous if ignored during the design phase. Understanding these risks are a critical factor for designing safe underwater play [46]. The intention is to design for depth and not to design for death by understanding changes in perception and motor skills [47], and orientation and movement control under the influence of Narcosis [48] (see Table 1): “Divers learn to ‘cope’ with the subjective impairments; yet the underlying behavioral effects and physiological symptoms remain” [49]. We developed a simplified preliminary guide for underwater play to describe the advisable level of interactions relating to the development of our prototypal interactive system for underwater play called Gravity Well. The purpose of this table was to give preliminary justification to a range of design decisions affecting the intellectual challenge, the mood, visual and auditory stimuli and the balance and coordination intensity that were based on the first authors’ knowledge as a commercial diver. The table was drafted through a process of cross-referencing factors including (but not limited to) pressure changes (depth), and the signs and symptoms of Narcosis (breathing air) to basic game design principals.

The documented effects of Narcosis include indicators of changes in mood; intellectual function, response to stimuli; and coordination and balance [26]. In short, narcosis produces a narcotic effect. This may include short-term and long-term memory loss [27] and unpredictable changes in behavior [28].

4. GRAVITY WELL

Gravity Well [3] explores how interactive technology can support the experience of underwater play. The system extends the interpretation of interactive technology used in underwater arts, aquatic sports, commercial diving and altered-gravity conditions (such as zero-G flights and activities at the International Space Station), which usually focus on enhanced human performance analysis or real-time environment feedback, and into the realm of human-aquatic-performance-analysis, and actual in-water, real-time robotic human motion mimicry.

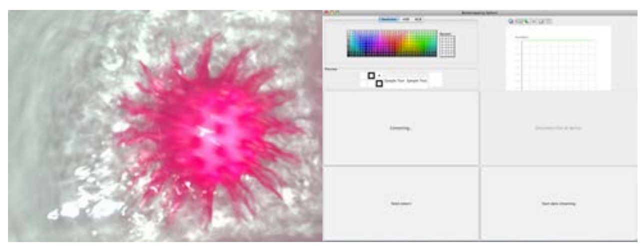

Figure 2. Explorer fish: propulsion and Bluetooth remote control testing.

The Gravity Well system offers novel ways of simultaneously visualizing and manifesting underwater play actions in real-time through direct engagement and communications with play objects. The catch is that players must get wet in order to experience and initiate the system. Interactions must occur between three dynamic bodily systems: the human body, the robotic body and the body of water to achieve underwater play. Each component of the interaction environment influences the overall performance and flow experience. Together, the interactive environment system for underwater play enables aquabatics: describing a state of being and a specific motility that is unique to this domain.

First stage testing of the Gravity Well system showed that it is possible to conceive of displaying aquabatics interactions outside of the body and in a non-virtual way (see Figure 2). It does this through play objects called ‘explorer fish’ which are tactile aquatic-robots capable of human performance mimicry. The Gravity Well system is experienced in a number of bodily ways:

through immersion, saturation, buoyancy, pressure-change and sensory stimulation through altered lighting, sound and touch.

The first phase design installation supports general public interaction. It comprises a shallow-water interface that is designed to attract attention, encourage curiosity for underwater play and build upon their imaginings for full-bodied interactivity. The underwater play interaction is a game of skill, and interpretation of the flow experience. The experience is augmented by tactile feedback from the play objects and the water. Spectators and players are provided a sensory rich experience through real-time movement control of play objects with internal lighting displays showing the level of underwater play vigor (see Figure 3).

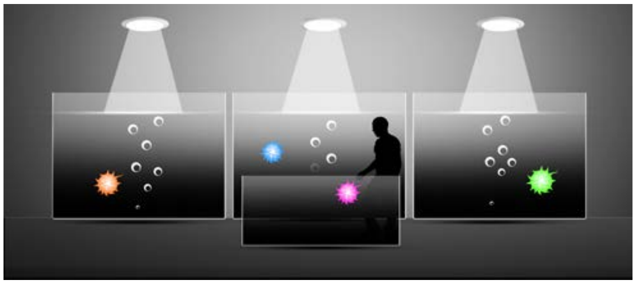

Figure 3. Gravity Well interactive installation setup

There are two types of play objects called ‘explorer fish’ (see Figure 4 and 5). The parent play object is called the ‘mother fish’. It measures the human-robotic-aquatic interaction and communicates the accelerometer and gyroscope data via Bluetooth through the water to control one or more remote ‘baby fish’. Spectators and plays delight in real-time movement control of the ‘baby fish’ movement’s response, which mimics and synchronizes with the ‘mother fish’. Together their actions behave like a collective school of fish, receiving direct commands from the parent. Lights augment the resulting movement. The more vigorous the interactions, the brighter the LED display.

Finally, the shallow-water ‘explorer fish’ has some in-built “personality” to encourage further interactions. For example, if a player attempts to drown the ‘mother fish’ by pushing her all the way to the bottom, the ‘baby fish’ will spin on the spot until you stop. If you stop interacting with the ‘mother fish’, the ‘baby fish’ will dim their lights, and eventually sleep. When they ‘wake up’, they vibrate and flash for a few seconds to let the player know that they are ready for underwater play.

Figure 4. Gravity Well’s current demonstration setup

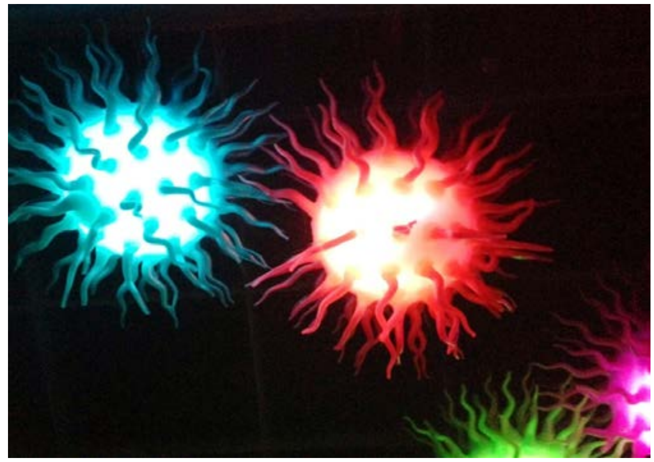

Figure 5. Explorer Fish silicon tentacle swimsuit enabling spherical aqua-robotic movement.

5. FUTURE RESEARCH

From art, entertainment, media, and sport to industry, we see the potential for underwater play research to contribute to the field of Physically Interactive *Robogames* (PIRG) [50] in addition to the potential for technology transfer supporting human performance in extreme environments. We see the framework of underwater play could support the direct application for occupational workplace operations and missions by supporting the perception and control of self-motion [51]. Furthermore, by finding solutions to the design and engineering challenges of the aquatic-human-computing interactions noted herein, towards a system which recognizes and replicates aquabatics we serve to enhance perpetual and motor skills for overall increased well-being [52].

Similarly, there is also the potential for underwater play to contribute novel human factors research supporting the rapid development of Aquabotics, Remotely Operated Vehicles (ROV)s, Autonomous Underwater Vehicles (AUV)s, and perhaps future personal submersibles and sub-sea habitat architectures [53]. Long term research goals seek to situate the phased research approach to underwater play in concurrent trans-disciplinary contexts to support and facilitate the design of robust and engaging experiences across multiple altered-gravity domains.

5.1 Next steps

As the Gravity Well underwater play robot is called an “explorer fish” as homage to Frank White who sees space explorers as “explorer fish”, venturing into space and, while creating new civilizations in three stages he calls Terra, Solarius and Galaxie, furthering new growth in their own evolution [54]. We plan the evolution of ‘explorer fish’ in these three stages also:

Terra: Hands – ROV (Recreational depths 0-3m)
hand-fish-H20 interaction operating independent fish

Solarius: Play Suit – ROV (Commercial depths 0-30m)
full-bodied H20 interaction operating remote fish school

Human – AUV (Commercial depths 0-100m)
autonomous school of fish recognizing aquabatics

Galaxie: AUV (Deep Sea depths >100m)
autonomous school of fish engaged in exploration

AUV II (Micro gravity environments)
autonomous school of fish recognizing aquabatics

AUV III (Multi gravity domains)
intelligent, creative autonomous school of fish able to interact, improvise and dance with another human

We see an opportunity to build upon our research of human-computing-aquatic system to design unique exertion games that facilitate full-bodied play experiences. Human performance analysis is still a challenge in extreme and altered-gravity conditions – particularly difficult is mapping human aquabatics in nature rather than controlled environments. We predict advancements in technology shall soon enable the development of more practical, reliable AUVs [55]. Future advancement in biotechnology, biomechanics and hyperbaric medicine shall also support new synergistic relationships with humans, augmenting performance, across new interactive environment domains [56]. A self-contained, intelligent, decision-making AUV is the goal of current research in space applications, underwater robotics and even nanotechnology [57]. We aim for a school of intelligent 'explorer fish' capable of long-range remote human motion mimicry for extreme performance and exploration [58]. Eventually, they will be intelligent and creative enough to dance on their own like a human through the aquatic and space domains.

6. CONCLUSIONS

These concepts are demonstrated by Gravity Well, an experimental test-bed for underwater play in a shallow-water installation as precursor demonstration systems for interactivity at depth. The long-view research objective focuses on extending human performance, experience and interactive systems across multiple altered-gravity domains.

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