Cerebrospinal Fluid Containers Navigator. A Systematic Literature Review

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Abstract. Robotics is used successfully in medicine. Mechanical gadgets assist the most intricate procedures, providing precision, error correction, stereotactic positioning, subtle controlling, and in-place visualization, among other benefits. However, few applications are designed to perform continuously embedded within the human body. Implants such as the peacemaker that works permanently inside the patient involve high risk. However, the risk is acceptable given the benefit that peacemakers provide when working correctly. The current proposal envisages a similar scenario. One in ten babies in America develops hydrocephalus. The abnormality is more incident in premature babies, but term babies are also subject to malady. Even adults develop a sort of hydrocephalus that keeps intracranial pressure at normal levels. Hydrocephalus quickly escalates from mild to severe due to cerebrospinal fluid circuit issues (CSF) issues. The only mechanism to alleviate the pressure within the CSF containers is to release the fluid progressively. Such as purpose requires opening the skull and locating a discharging device – diverting shunt – that goes through the brain mass and reaches the ventricles. This invasive gadget grants a way out to liquid but is not always infallible. The shunt often fails, and reiteratively opening the skull is the method to pursue. Shunted patients with more the 100 brain surgeries have motivated the campaign no-more-brain-surgeries promoted by the Hydrocephalus Association (https://www.hydroassoc.org/join-us-as-we-say-nomorebs/).

This document registers a revision on immersive robotics and sensors that allow us to create a submergible device capable of exploring 3D printed macro models of the CSF containers. This first approach will serve as a testing land to understand fluid mechanics, navigability, and blockage removal techniques from inside a model mimicking the brain in healthy and abnormal conditions. Once this is accomplished, we intend to

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miniaturize the device and check the feasibility of a medical application that controls cerebrospinal fluid abnormalities while avoiding recurrent surgery.

Keywords: CSF · Hydrocephalus · Shunting · Submersible robots · Brain pressure · CSF analysis · Medical imaging

1 Introduction

The inclusion of technology in medicine has optimized the resources and empowered physicians' decision criteria to benefit the patients. Initially, the tech-based gadgets played an assisting role that speeds up processes and granted healthcare providers leading insights that favored verdicts' accuracy [4]. Soon, the technology became more intrusive that machines now perform specific procedures where high precision is crucial [14], or the reproducibility of human operators is highly compromised [7].

The technology to study and intervene in the brain has been thoroughly tested and commercialized. Devices to visualize the anatomy are prolific and have made the radiology departments the busiest units in hospitals and clinics. Imaging systems are not intrusive but are limited to diagnosing static representations of the structure inside the skull. At the same time, dynamics remain mostly hidden even with sophisticated tools such as diffusion and functional MRI [1].

Some other technology interfaces the brain to recover sensor capabilities [5], and specialized research is venturing into the recovery of motor functions using electromyography to provide signaling to a human part that has lost motion or to a robotic prosthesis [10]. Interfacing the brain through electromyography is not directly touching the brain. However, its implementation requires a learning process that will modify neuronal interaction, which enlights the complexity of the organ.

The most intrusive medically approved devices working on the brain are the ventriculoperitoneal shunt (VPS) valves used to release pressure created by the accumulation of cerebrospinal fluid namely hydrocephalus [9]. The original device was a passive tube surgically implanted in the brain ventricles. Modern valves are also intrusive but can regulate the fluid using closed-loop controls and communicate with external devices for monitoring purposes [13].

The insertion of a VPS is the most common treatment for hydrocephalus, with approximately 30,000 procedures performed annually in the USA. Complications in adults can range from 17% to 33%, leading to hospital readmissions for treating complications that increase hospital costs by 50 million dollars per year [7].

Although the technological advances in shunting valves, the abnormality yields 750 new cases per 100,000 live births worldwide, and some HC patients may have more than a hundred surgeries in their life span.

The hydrocephalus association annually releases grants to study the HC precursors and supports research to alleviate an old problem with no solution. Our research aims to explore the phenomena associated with the HC abnormality from the inside by creating a 3D replica of the CSF space and navigating that structure while gathering data that presents consistent information to understand HC genesis. We also envisaged the possibility of taking the CSF navigator inside the brain after miniaturization, where this active device might localize blocking particles and dissolve them safely.

This systematic literature review investigates edging technology in submersible robots, buoyancy, propulsion, visibility in watery environments, wireless video transmission, autonomous displacement, light-based boundary detection, and remote control.

This paper is structured as follows. Section presents the SLR methodology used in this research. Section 3 presents the results of the research that allowed us to solve the research questions. Section 4 discusses the method and results presented in the previous sections. Section 5 proposes future works based on this research. Finally, Sect. 6 concludes the paper.

2 Materials and Methods

This paper applies the guidelines proposed by professor Barbara Kitchenham in her article: *Procedures for Performing Systematic Reviews* [6]. The guide focuses on how to perform a Systematic Literature Review (SLR) with referential coherence and selectiveness. It consists of 3 parts:

1. Planning. We state the justification, needs, and search strategy of the SLR.
2. Execution. We perform document search, quality filtering selection, and extraction of relevant information.
3. Reporting. We consolidate the information, discuss usability and integration possibilities, and postulate guidelines for further work.

2.1 Research Questions

This study is based on the following research questions:

- RQ1. Which is the best micro-robot design to achieve stability, buoyancy control, and harmless navigability in a waterly-closed environment?
- RQ2. How to displace a submergible robot while optimizing hardware?
- RQ3. How can a robot communicate with the outside while immersed in a fluid?
- RQ4. What are the sequelae in patients who suffer hydrocephalus secondary to shunting procedures?

Search Strategy. Kitchenham [6] suggests identifying relevant aspects in regards to population, intervention, outcome, and experimental design of the gathered data.

- **Population**. The population refers to a specific group of people who suffer hydrocephalus. So, the keywords are `non-invasive hydrocephalus treatment` or `CSF circuit` or `hydrocephalus` or `Complications after shunt` or `Shunt procedure`.
- **Intervention**. The technologies that address the specific approach are robotics; in particular, soft robotics. Also, submersible robots, buoyancy, displacement, the propulsion strategies and hydrophobic materials. Also biomimicry suggest to solve complex problems by mimicing designs adopted in the nature. Then, the keywords are `soft robotics` or `submersible robot` or `micro robot bio-mimicry` or `hydrophobic materials` or `submerged nanobots` or `buoyancy underwater`.
- **Outcome**. The relevant outcomes are associated with moving devices inside the fluid, autonomous microrobots, and reliable communication inside a fluid. Therefore, the keywords are `kinetics underwater` or `communication underwater` or `robot navigability`.
- **Experimental design**. A stage of development that we partially accomplished in this delivery. Device creation and records of operation will be detailed in the next delivery of the project.

Selected Journals and Conferences. The research articles were found in the following digital databases: Scopus, IEEE Xplore, Springer Link, Oxford, and Science Direct. We filtered the search for a range of time between 2011 to 2020, as shown in Table 1.

2.2 Study Selection Criteria

We employed inclusion and exclusion criteria in the selection process. Refer to complementary information for more details. The inclusion and exclusion criteria derive from the research questions.

The inclusion criteria are as follows:

- **IC1:** Submersible micro-bots capable of realizing underwater manipulation or monitoring their surroundings
- **IC2:** The submersible robot's design has its mechanical structure and electronic system isolated from surrounding fluid or covered by hydrophobic materials
- **IC3:** Studies that show the shunt procedure's effects and the complications in patients with hydrocephalus

The exclusion criteria are as follows:

- **EC1:** Submersible robots using a external structure or propeller for its locomotion

Table 1. Search process documentation

Database	Years covered by search	Search strategy
Scopus	2011–2020	TITLE-ABS-KEY((“buoyancy”) AND ((“underwater”) OR (“soft robotics”) OR (“submersible robot”)) AND (LIMIT-TO(SUBJAREA, “ENGI”)))
Science Direct	2017–2020	((“circuit CSF”) AND ((“Hydrocephalus”) OR (“Complications after shunt”) OR (“Shunt procedure”) OR (“non-invasive hydrocephalus treatment”)) AND ((“hydrophobic materials”) OR (“robot navigability”)))
IEEE Xplore	2016–2020	((“robot navigability”) AND ((“buoyancy underwater”) OR (“submersible robot”) OR (“communication underwater”))) AND (“microrobot”)
Springer Link	2015–2019	((“micro robot bio-mimicry”) AND ((“kinetics underwater”) OR (“communication underwater”)) AND ((“submerged nanobots”) OR (“Submersible robot”)))
Oxford	2000–2020	((“circuit CSF”) AND ((“Hydrocephalus”) OR (“Complications after shunt”) OR (“Shunt procedure”)))

– **EC2:** Non-submersible robots
– **EC3:** Informative articles related to hydrocephalus without measurement data

2.3 Study Quality Assessment

After filtering with the inclusion and exclusion criteria, a total of 29 articles remained on the list. 13 articles passed a second selection phase from the original list, where we took care of duplicate or similar content as presented in Table 2. In addition, we classified the pre-selected articles into the needed modules as shown in Table 3.

Table 2. Pre-selected articles

Database	Retrieved	Duplicated	Pre-selected
Scopus	12	2	5
Science Direct	5	1	2
IEEE Xplore	8	1	2
Springer Link	3	0	3
Oxford	1	0	1
Total	**29**	**4**	**13**

Table 3. Definition of study designs modules

Module	Basic type	Definition
Treatment's effect	Secondary studies	A quantitative study in which shunting procedure effects in patients suffering hydrocephalus can be visualized based on results data
Communication	Experiment	An experiment testing submersible robot communication. Pertinent and substantial data are extracted from the submerged system
Motion	Prototype	A submersible robot prototype capable of generating its motion using the surrounded fluid and avoid any filtration that could damage internal mechanics
Structure's design	Observation prototype experiment	A study comparing robots' physical structure's prototypes from which the best physical design could be inferred. In addition, an experiment in which the robot does not harm or change in any way the environment where navigability takes place

2.4 Data Extraction

Important information was extracted from pre-selected articles as follows.

- Title, authors, journal or conference, publication details (year, country, reference)
- Article database where it was found
- Topic area
- Problem trying to solve
- Objectives
- Methods (used to provide a solution)
- Results

2.5 Data Synthesis and Quality Verification

We synthesized the pertinent data after classifying the articles in operative-wise modules obtaining the results presented in Table 4. This table exposes verification criteria (VC) that enlighten the source classification.

After applying the quality criteria, we have selected those documents that meet the requirements of the study. Table 5 presents the number of selected works by the database. In addition, Table 6 summarizes the journals or conferences of selected articles, their Scopus h-index, and their country.

3 Results

3.1 Shunting Sequelae

According to the literature review conducted by Hebb and Cusimano [4], 38% of shunted patients presented complications after valve implantation, 22% underwent additional surgery, and 6% developed a permanent deficit or died. Among

the most insidious reasons for the post-surgical complication, non-hemorrhagic stroke was suffered by 5 out of 37 individuals. At the same time, the deadly postoperative cerebellar hematoma was present in out of 9 patients.

An alternative option to the invasive shunting is the CSF puncture; in that procedure, specialists drain 40 to 50 mL from the lumbar cistern to alleviate intracranial pressure. Using this alternative, according to the results shown in the literature review done by Hebb and Cusimano, patients who had controlled and continuous drainage avoided unnecessary surgery in the future [4]. Nevertheless, since CSF production is continuous, the puncture is not a long-lasting solution.

3.2 Robotics

Biomimetics is the science that studies the behaviors or characteristics existing in nature, aiming to mimic designs and functions that could solve problems in diverse fields. An example is the biomimetic robots is proposed by Wissman et al. [14]. The authors built a cupule that provides fishes – and the robot as well – with rheotaxis. This property characterizes how a body interacts with a current of a fluid. The rheotaxis will yield a value around zero (static in fluid) depending on the body moving along with (negative) or against (positive) the current. The measuring cupule is 5 mm in height and has a sensitivity of 0.5 pF (capacitance vs. tip deviation). The transducers are embedded metal plates in a soft silicone body located inside the body cupule [14].

Table 4. Quality criteria per module

Module	Quality criteria
Treatment's effect	**VC1.** Does the study contains quantitative information related to people who were treated with a shunting procedure?
	VC2. Is it mentioned in an explicit way which one are the consequences after receiving a shunting treatment?
	VC3. Does the article consider more than 1 person to conclude secondary effects after received a hydrocephalus treatment?
Communication	**VC1.** Is there a communication immersed in a fluid?
	VC2. Does the article mention at least one communication technique?
	VC3. Is it shown experimental communication results?
Motion	**VC1.** Is there a submersible robot using the external fluid to its locomotion?
	VC2. Does the article show experimental results which justify the motion way?
	VC3. How were isolated the internal structure?
Structure's design	**VC1.** Is there safe navigability that avoids crashing or damage its external environment?
	VC2. Does the article mention which material the robot is?
	VC3. Does the article justify why the robot's shape?

Table 5. Selected articles

Database	Pre-selected	Selected
Scopus	5	4
IEEE Xplore	2	1
SpringerLink	3	2
ScienceDirect	2	1
Oxford	1	1
Total	**13**	**9**

Table 6. Selected journals and conferences

Name	h-index	Country
Neurosurgery	198	United States
Chemical Engineering Journal	223	Netherlands
Journal of Marine Science and Engineering	22	Switzerland
Scientific Reports	213	United Kingdom
IEEE Int. Conference on Robotics and Biomimetics, ROBIO 2016	12	United States
Microsystem Technologies	63	Germany
Journal of Intelligent and Robotic Systems: Theory and Applications	77	Netherlands
Sensors	172	Switzerland
Neurologic Clinics	82	United Kingdom
Science Robotics	50	United States
Total	**1112**	**Worldwide**

Soft robotics is a subfield of robotics where the materials of the robots built are as similar as possible to those found in a living organism. The uses it has are varied, such as prosthetics, medical monitoring, and motion tracking. For the mentioned cupule, resistive and capacitive sensors are used due to their usefulness in soft robotics, these are built using conductive particles embedded in the rubber.

A robotic system incorporates six thrusters grouped by two that keep track of displacements in three axes providing the robot with an accurate localization in floating devices. The system does not need external references and represents the most sophisticated proposal regarding navigation among the reviewed material.

3.3 Detecting Obstructions

There are different types of ways to detect obstruction in the aquatic environment such as:

1. Lateral line system. It is a sensory organ of some marine animals. Fishes employ it to detect the movement and vibrations of the surrounding water, avoid collisions, orient themselves about water currents, and locate their prey.
2. Reconfigurable AUV. Yue et al. [16] refer to underwater intervention with autonomous management through performing a search and manipulation under the sea.

3.4 Buoyancy

Finding suitable materials is crucial since the robot must repel water when navigating; nonetheless, the system should control liquid absorption/rejection and immersion deepness. Superhydrophobic coatings have diverse applications such as corrosion protection, water separation in aquatic devices, and submersible robots. Suyambulingam et al. [12] present a superhydrophobic coating is developed using porous Zinc Oxide (ZnO) and copper stearate (CuSA2) nanoparticles, using an economical sputtering method. The authors assert that any surface with surface energy lower than 0.07 Nm1 will float and get repelled from the surface, which is the primary reason for hydrophobicity. Thus, ZnO, and CuSA2 material was used to make a superhydrophobic spray coating with porous particles in a single step. The ZnO/CuSA2 coating has a high WCA level of 161, indicating its high hydrophobic effect. It floats for approximately four months and has a high loading capacity, almost 333 times its weight.

SUR II is a circular autonomous ROV (Remotely Operated Vehicle). The system uses water jet propulsion for its displacement and employs thrusters to assert direction. The SUR II produces little noise as it implements a Kalman filter for data gathering. The SUR II design features a circular structure that provides robustness and maneuverability beyond the specification of any other shape. The invertors accomplished displacement through an equilateral triangle that distributes water to propellants, which produces a more efficient operation; however, it requires more complex algorithms. [15]. The authors fabricated the supporting parts in polylactic acid for 3D printing, making the case biocompatible and light. Additionally, the material is collected from renewable sources; therefore, it has a lower cost than other suitable hydrophobic and low-density materials. The case consists of two hemispherical hulls that protect the electronics. These hemispheres are light, so a few air interchanges achieve the robot's buoyancy. The hemispheres are secured with 10 mm screws, and these are attached to the box, making the height of the air box adjustable.

In the center of the robot platform, the authors created air chambers to aid buoyancy. In [16], the system uses electrolysis on the surrounding water to obtain hydrogen and oxygen gas and direct it to the air chambers. The authors justified their work based on Archimedes' Law: "Archimedes' Law: $FB = \rho g V$ where g is the gravity $g = 9.81\,\mathrm{m/s^2}$; V is volume of the hydrogen and oxygen which is collected by the grooves; ρ is the fluid's density – $\rho = 1.0\,\mathrm{g/cm^3}$ for water –. If we ignore the compression of the gas, the maximum of V_{max} is equal to the volume of the grooves. $Vmax = 2Vgr = 2 \times 20 \times 5 \times 6 = 1200\,\mathrm{mm}$ and the maximum buoyancy force $FBmax = 11.8\,\mathrm{mN}$".

Sun et al. [11] present two AUV prototypes. The first design has oil capsules placed within the case, while the capsules reside out of the main body in the second version. The designs have different hydrodynamics, and thus, their energy management and durability are different. The researchers submitted the designs to inertia and viscosity; the first design is frictionless. In the second version, the friction is present with variable intensity depending on the fluid type. The Authors concluded that prototype number one was more resistant than prototype two.

There is another type of autonomous vehicle found in the literature. Capocci et al. [2] introduces an ROV design consisting of a general box shape and a flotation section at the top. The thrusters and equipment are purposely located below the main structure to assert stability and separate the center of gravity and the flotation center vertically. Such as design reduces noise produced by fluctuations in the water and rocking.

Christianson et al. [3] introduce a submersible robot with neutral buoyancy that reduces the energy required for displacement by introducing air in laterally located chambers. The robot's speed is low compared to others of the same kind; however, the DEA is not opaque and does not require electrical membranes. The device is also provided with an arm that creates resistance to free movement.

4 Discussion

The study of submersible robots forced us to consider different modules, as shown in the previous section. The design selection will define the subsystems that better suit the purpose of the current work. Multipurpose designs are attractive since energy consumption remains an unattended challenge. Therefore, robots with multifunctional modules – meaning no real distinction between buoyancy, propulsion, sensor, and mechanical systems – will be prioritized. Bulky types of frames were found to be disadvantageous due to dragging. The drag coefficient in non-hollow objects is equivalent to the cross-sectional area. The fluid passing rapidly over bulky objects causes a turbulent flow regime [2], which is not desirable if thinking that this device may navigate in biological containers. The literature suggests spherical objects with a drag coefficient below 0.4 [15].

The inspection ROVs have in common the thrusters to move, which is essential to maneuver underwater or maintain their position; these thrusters vary according to the specifications, such as DC motors with brushes, brushless, coupled by magnetism, or driven by tires (in amphibious designs). The medium class ROVs have hydrodynamics developed to improve their movement underwater; they have a square internal structure divided into an upper buoyancy block and the thrusters and equipment below. Such as disposition yields better stability by distributing the center of gravity and buoyancy in the vertical axis. [2]. These devices are primarily spherical, and a center airbox achieves buoyancy [3,15].

Movement depends on the surface's texture, and the resistance of the material in contact with the surrounding liquid [14]. A spherical-shaped robot can use three vectorized thrusters in the three axes X, Y, and Z, through 3 spaces that

allow the entry and exit of water. A triangular base is used to feed the thrusters connected to 2 servomotors to move horizontally and vertically [8,15].

Communication is essential to recovering information collected by a robot. Coarse wavelength division multiplexing (CWDM) devices enable data transfer from several channels for sonar, cameras, navigation, control, and other sensors. Some research prototypes feature fiber optics for communication; nevertheless, twisted pair cable is the most common and preferred [2]. Bioluminescence is also an option for communications in liquid environments. In robotics, optical communication can be of help when radio waves cannot be used or are not favorable [3].

Finally, the coating is essential. According to the literature, polymer materials have the benefits of low weight, no degradation in water, and low-cost [2]. Alternatives mention zinc oxide (ZnO) and Cation efflux system protein CuSA2 to make superhydrophobic spray coatings on porous surfaces [12].

5 Future Work

This SLR aims to settle the bases for building a lower-risk solution that provides better insights into hydrocephalus mechanisms. We propose a micro-robot with a spherical design preventing damage to the sounding structures. The device will use hydraulic flows generated by single-engine instrumentation inside the micro-robot. The envisaged structure has several advantages, such as placing an air chamber in the center that allows better buoyancy and stability. The structure will allocate an IP camera with the capacity of sending frames – single or streaming – wirelessly. Light-based echolocation prevents collisions with the required speed and enables the reconstruction of boundaries in those regions where the camera does not have enough resolution.

6 Conclusions

Shunting complications include subdural hemorrhage or effusion, infection, seizures, focal neurological deficits, shunt malfunction, and death. For these reasons, further work is proposed based on this systematic literature review. A micro-robot that inspects CSF containers is envisaged. Firstly, to learn about the abnormality genesis in a synthetic macrostructure that serves for more reliable simulations. Secondly, with a possibility to navigate inside the skull after miniaturization and when complex issues about energy supply are overpassed. According to the SLR, robots with a spherical shape and buoyancy control are the best option for energy-saving displacement and unharmed navigability strategies. During this review, we also discovered that liquid filtration and internal damage could be overcome by using hydrophobic materials that are also biocompatible.

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