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An Energy-Efficient Context Aware Solution for Environmental Assessment [⋆]

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Abstract: The paper focuses on presenting the advantages of context aware cyber-physical systems through an experimental platform capable of assessing its surroundings and self-performing decisions. The context aware paradigm is present in the control law implementation with various advantages such as energy efficiency as well as in the environmental measurements that trigger the robot to perform context-relevant decisions. The platform provides high versatility and the results presented throughout the study can be adapted to a manifold of multidisciplinary fields.

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Keywords: Submerged Vehicle, Context Awareness, Environmental Assessment, Event-based control

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1. INTRODUCTION

A cyber-physical system is the place where the virtual space converges with the physical world. One of the first complex definitions of a cyber-physical system is presented by Rajkumar et al. (2010) as "physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core".

Real life data is the pivot point in any cyber-physical system. The ability to acquire information regarding a multi-dimensional operating context empowers the tailoring of services and solutions, customized for any specific process objective. The current industrial revolution, widely known as Industry 4.0, is built around protocols such as Internet of Things and cloud computations, embedding the full power of smart devices in the manufacturing field, as presented by Zhong et al. (2017); Lele (2019) and Munirathinam (2020). An overflow of process related data is merged into a single core, creating self-sustainable, adaptive and context aware canvases. Context awareness in cyber-physical systems represents a key element in the industrial future, leading to an intrinsic ability of decision making based on information provided by the smart sensor networks as presented by Pradeep and Krishnamoorthy (2019) and Alegre et al. (2016).

Examples of cyber-physical systems can be found by analyzing day to day life, from autonomous cars, smart grids, implanted medical devices, robotic surgeries, etc. Papers such as Dey et al. (2018); Letichevsky et al. (2017); Yuan et al. (2019) introduce the reader to a wide variety of multidisciplinary applicability which allows the integration of such systems in fields like transportation, medicine, energy, defense, manufacturing, industry, etc.

The paper focuses on a cyber-physical system consisting of a submerged vehicle capable of assessing environmental data. The inspiration of the work lies in Autonomous Underwater Vehicles (AUV), vehicles without any physical connection to their operator. These are useful in performing underwater surveys such as mapping the ocean's floor, detecting high levels of pollution, petrol leaks, vessel obstructions or tracking marine currents and fauna migrations (Choi and Yuh (2016)). AUVs are scarcely available on the market, being extremely expensive and with limited possibilities. The current study, proposes a versatile, small scale submersible that can be built with on the shelf components at a reasonable price. The submersible is fully customizable with sensors dedicated for environmental assessment, depending on the particularities that are desired to be monitored. The device communicates bidirectionally with an external server. The server sends information such as reference position/velocity and receives the current position/velocity of the robot as well as measurements of different environmental aspects. The robot is context aware and autonomously performs decisions related to its positioning as well as the necessity of data share with the server. The cyber-physical concepts are integrated in both sensing and manipulation possibilities which are performed locally, inside the robot, while control tasks and

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observability are performed by a server that analyzes real-time data across the network.

The versatility of the current study lies in the wide applicability of the developed submersible in a manifold of research fields. Furthermore, the robot is capable of transiting both Newtonian and non-Newtonian environments, featuring a complex control strategy that is able to successfully guide the robot through both types of fluid, broadening even more the large spectrum of possible applications.

The paper is structured as follows: Section II focuses on explaining the concept of context awareness and its necessity in cyber-physical systems, Section III presents the description and the versatile navigation model of the submersible, while Section IV explains the context aware motion control algorithm as well as its benefits. Finally, Section V concludes the paper.

2. CONTEXT AWARENESS IN CYBER-PHYSICAL SYSTEMS

An initial definition of context is provided by Dey et al. (2001) as "any information that characterizes a situation related to the interaction between users, applications, and the surrounding environment as useful". In other words, a context can be any data useful in characterizing the entity itself or any information relevant for the current setting (Moumane et al. (2016)).

Industry 4.0 is a compilation of state of the art scientific advances used to enhance the manufacturing process. It is desired to diminish even further human interactions through the usage of smart manufacturing systems and cloud integration. State machines, self-monitoring processes, machine to machine communications or decision making are just a few key factors of the industry of the future. Interconnected networks share information, data and decisions over the Internet of Things protocol. Distributed systems are the new manufacturing standard in control engineering for the industrial field. Novel cloud architectures featuring a multitude of interconnected sensors and actuators provide an overflow of data, registering the context in its entirety (Truong and Dustdar (2009); Perera et al. (2015)).

The improved automation technologies are able to gather a large amount of varied data with different degrees of importance for the output of the process. A necessary feature in any context aware system is the decision making protocol. This can be related to control decisions, but also represents a powerful tool in identifying relevant information and separating redundant or clutter-type of data. An unnecessary amount of data can lead to an overburden of the system's core as well as bandwidth allocation in network sharing and energy efficiency. Introducing distributed decision making modules allows the filtering of the data locally and the transmission of filtered information. The context aware architecture has data filtering as its lowermost layer and contextually relevant information in the upper layers (Lu (2017); Frank et al. (2019); Wollschlaeger et al. (2017)).

The context manager analyzes the acquired data and sorts it with respect to its relevance on the process' output or on obtaining a desired objective. A schematic of context management principles is shown in Fig. 1. A context map is generated for each system objective based on current and regressive information. The decision making module analyzes the effect of the acquired information on the manipulated and controlled variables, separating it into different groups. For example, the green points represent pieces of information with the higher relevance in reaching the objective of the system. The layabout pairs are depicted with orange and represent information irrelevant for the current context, whereas the red bullets encapsulates data that hinders reaching the objective. Each objective has a data map showing its relevance towards the particular goal. Furthermore, the objective and its corresponding map is analyzed by an event detector that determines whether specific actions will cause the movement of bullets from the green area to an undesired area, determining if a particular action should be triggered. After the event-based controller is activated, the process variable is manipulated according to a predefined control law. Finally, the context manager evaluates the newly created context and the actions are repeated (Perera et al. (2014)).

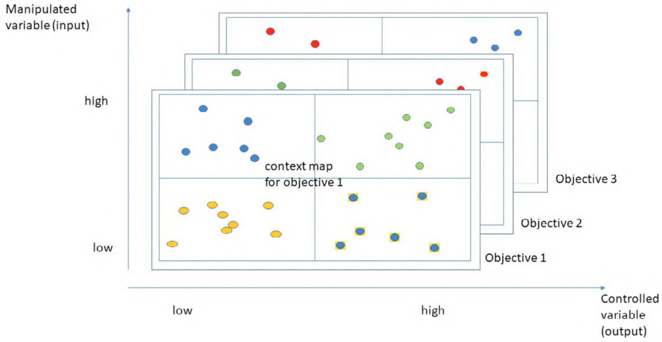

Fig. 1. Context manager

Context awareness is intrinsically encapsulated in the concept of event based or event driven control. The control strategy maps the system's context and determines if the control law should be used to compute a new manipulated variable. The objectives of the process are always taken into consideration inside an event detector module. When the process' context map triggers an event, a control input generator handles the computation of a new manipulated variable, ensuring that the process reaches the objective (Grüne et al. (2014); Miśkowicz (2015)).

3. SUBMERGED VEHICLE

3.1 Description of the experimental unit

The hull of the robot is 3D printed with an aqua-dynamic, ellipsoidal, shape inspired from full size submarines. The size of the robot used for this study is 0.09m in length and 0.03m width, but the shell can be printed using any size that respects the length to width ratio. The robot is equipped with a 3 blade 4mm propeller manufactured by Graupner that generates the thrust needed for navigation. If the submarine is recreated with a larger scale, the same propeller can be reused for sizes up to twenty times larger.

Fig. 2. Submerged vehicle

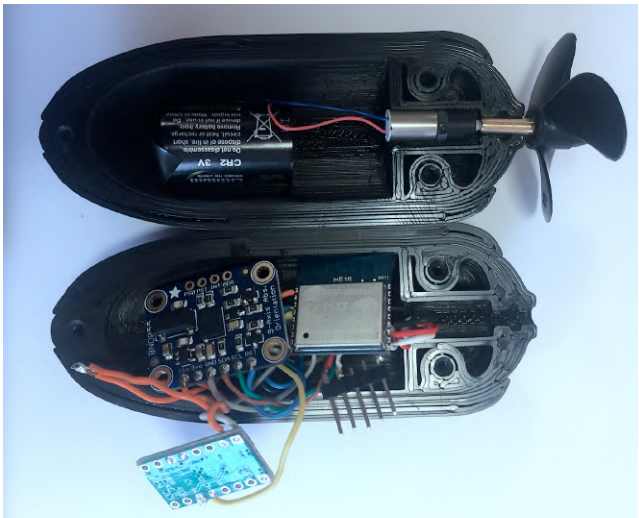

Fig. 3. Embedded electronics

Fig. 2 presents two snapshots of the submersible from different perspectives.

The submersible is designed using widely available electronics. The opened submersible is presented in Fig. 3. The hull houses several modules, each for a different purpose. The two pieces are glued together using gasket sealant to be fully watertight, opening and resealing only when the battery should be replaced.

The core unit of the submersible is the ESP8266 microcontroller, equipped with a built in WiFi module. The ESP8266 is the manager of all the other components and represents the unit that acquires/processes data as well as performing the control task. The context manager is implemented inside this unit, one of its main capabilities is to create context maps and determine the degrees of relevance of the acquired data. The submersible communicates with an external server via WiF using a secure TCP/IP protocol. The data share is bidirectional: the submersible receives desired operation modes such as navigation with a reference velocity or to a specified location relative to its current position, while the server receives the current position/velocity and data acquired from the environment. Environmental data acquisition shall be discussed in detail in Section 4.2.

The velocity and displacement of the robot are computed based on data acquired from the BNO055 9 degree of freedom Inertial Measurement Unit manufactured by Bosch. The motion data from gyroscope, accelerometer and magnetometer is fused on the ESP8266 microcontroller and both velocity and position are computed locally. Hence, the robot can navigate autonomously, closing the control loop without the need of the server.

The propeller is connected to a 10x6mm DC motor and a DRV8833 driver. Applying PWM signals between 0 and 5V to the motor rotates the propeller, thrusting the submersible. The propeller can rotate in both directions, allowing forward and backward movements as well as braking possibilities.

The elements are fed by a CRC232 lithium-ion battery with a TPS61090 power booster circuit that ensures a nominal operating voltage between 2.7V and 3V until the battery is fully drained. The robot can go into sleep mode when unused, command given by the server.

The server specific tasks are:

(1) send *sleep* or *awake* commands,
(2) set the robot's operating mode:
  - **manual**: send a constant PWM value to be fed to the propeller,
  - **auto**: send a reference velocity or position, the robot will navigate using a local control law for velocity/positioning
  - **explore**: a fusion between the *auto* mode and environmental assessment with the ability to halt the robot for a period of time in areas where changes are detected
  - **emergency**: overrides all other operating modes and halts the robot
(3) receive and log data related to the robot's velocity, position, operating PWM and environmental measurements.

The robot's tasks are:

(1) listen to commands from the server,
(2) navigate the environment with respect to the operating mode,
(3) compute the voltage to control the propeller's rotation with respect to apriori defined control law, needed in *auto* and *explore* operating modes, such that the imposed objective for velocity or positioning is fulfilled,
(4) create context maps for objectives such as velocity/position and environmental assessment,
(5) send relevant information to the server, avoid redundant and irrelevant information.

An important mention is that data is sorted locally on the ESP8266 unit, using the context manager. This brings several improvements in bandwidth allocation and energy efficiency.

3.2 Generalized motion model

The submarine has been initially developed with the purpose of modeling the interaction between non-Newtonian fluids and a transiting object. Non-Newtonian fluids don't follow Newton's law of viscosity, with viscoelastic characteristics that change with respect to external forces. A generalized navigation model has been developed, valid for both Newtonian and Non-Newtonian environments based on fractional calculus, a powerful tool that accurately described physical phenomena such as viscoelasticity. More information related to the initial application of the submersible and the developed model are presented in Birs et al. (2019); Birs and Muresan (2020); Ionescu et al. (2020).

The robot has been updated and some parts have been redesigned for the purpose of using it in different fields and exploring its sensing capabilities as well as its nature as a cyber-physical system.

The position navigation model has been developed in the previously mentioned studies as

$$H_{FO-Pos} = \frac{0.1}{s(0.005682s^{1.7263} + 0.11031s^{0.8682} + 1)}. \quad (1)$$

The velocity model can be easily obtained from the positioning transfer function by removing the $1/s$ integrator. The model from (1) holds for different scales of the submersible, the fluid - object interaction principles being encapsulated in the fractional order transfer function. Note that the powers of the Laplace operator s are 1.7263 and 0.8682 representing fractional, non integer, orders of the differinteger operator. The advantages of using fractional order models is the better representation of physical phenomena in a complex transfer function, but with a reduced number of parameters.

A control law is developed for the navigation model from (1) such that the robot is able to navigate to a desired position or with a reference velocity, sent by the server. Since the model is a fractional order transfer function, only a fractional order controller is suitable for controlling the process. The control law is used only when the robot is operating in *auto* or *explore* modes. The fractional order transfer function used for control purposes is

$$H_{FO-PD} = 65.0028(1 + 0.0305s^{0.6524}). \quad (2)$$

4. CONTEXT AWARE MOTION CONTROL

The submersible is context aware from two point of views: control law computation based on context (regression data) and environmental measurements of its surroundings.

4.1 Event based control - a solution to energy efficiency

Event based control is the natural solution to context awareness paradigms of control laws. Discrete-time systems are usually sampled in a periodic manner, known as Riemann sampling. In traditional approaches, after a period of time T_s has elapsed, the control law computes a new value for the manipulated variable, regardless if it will influence or not the state of the output. For example, in a steady state regime, the control signal is usually constant and a new value is computed every T_s seconds that is identical to the previous control value. This means that the effort performed to compute the new control variable futilely overburdens the core of the system and it also drains the battery (Aström (2008)).

A solution to this problem lies in discrete-time control laws implemented with aperiodic sampling, known as Lebesgue sampling. Event-based control strategies are based on Lebesgue sampling, every control computation being triggered by a context. A context manager defines events that should trigger new computations of the control signal, known as event detectors. The laws are customized for the need of every process and usually involve the error value being inside a predefined interval and a safety condition, ensuring that at least one control value is computed in an apriori defined maximum time period. The objective of the event-based control strategy is to reach the objective defined as the reference of the process (Grüne et al. (2014)).

The event-based solution is particularly useful for the submersible case study in order to avoid the computation of the control law taking most of the CPU allocation, the control signal being computed locally on the submersible. Traditional, non-event-based control algorithms should run asynchronously to all other tasks such as data acquisition, position computation and server communication. However, the event-based implementation removes this constraint through the usage of variable sampling techniques. Another benefit is the improvement of energy efficiency. Experimental tests suggest that using a context aware control strategy such as event-based control, the battery life is improved up to 4 times.

The fractional order controller from (2) is implemented on the experimental robot using the strategy from Birs et al. (2020) and the results are presented in Fig. 4 and Fig. 5 for Newtonian and non-Newtonian fluids. The experiments involve the robot operating in *auto* mode and receiving the 0.4m reference position from the server. The 0 position is considered the position of the submersible at the moment the new reference value is received. As can be seen in the two figures, the robot successfully reaches the desired 0.04m position in both environments, while also being aware of the control context.

4.2 Environmental awareness

The second context aware aspect of the cyber-physical system is the environmental assessment realized in the *explore* operating mode. An additional module is used to measure fluid impedance that can detect environmental changes. The *explore* mode implies data acquisition regarding the surroundings with a constant velocity (the control law is implemented using the previously described algorithm) and if a change is detected, the robot halts at the problematic area in order to register more data. The decision whether the robot should halt for a few seconds is realized internally, by the ESP8266 core unit.

As a case study, a Dropsens 550 impedance sensor has been attached to the robot, as can be seen in Fig. 2. The sensor may be replaced with any hardware that fits

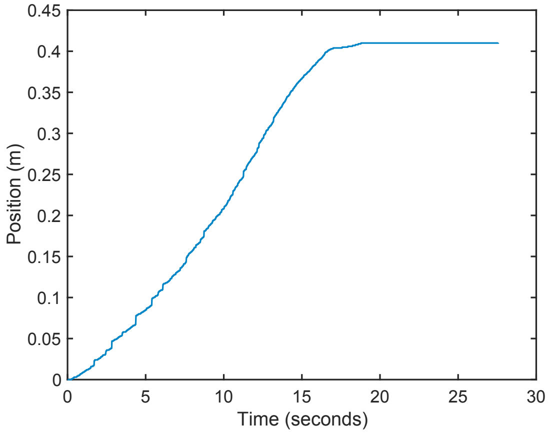

Fig. 4. Submersible going to a desired position in a Newtonian fluid

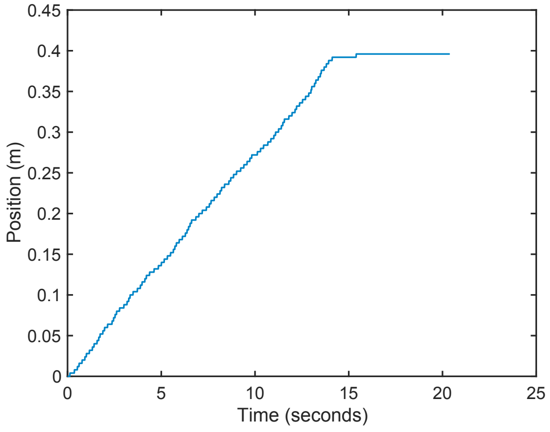

Fig. 5. Submersible going to a desired position in a Non-Newtonian fluid

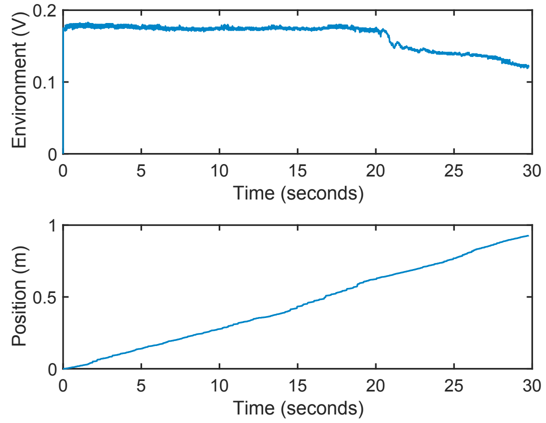

Fig. 6. Environmental assessment of gradually changing context

the purpose of the submersed investigation, as long as it doesn't significantly alter the physical properties of the submersible.

In the test scenario shown in Fig. 6, the robot navigates a non-Newtonian environment with a constant environmental impedance between 0 and approx. 18 seconds. It can be observed that the environmental values are constant until 18 seconds, but afterwards there is a gradual change in the voltage. The context manager implemented inside the robot decided that the robot should continue it's movement in order to further inspect the surroundings.

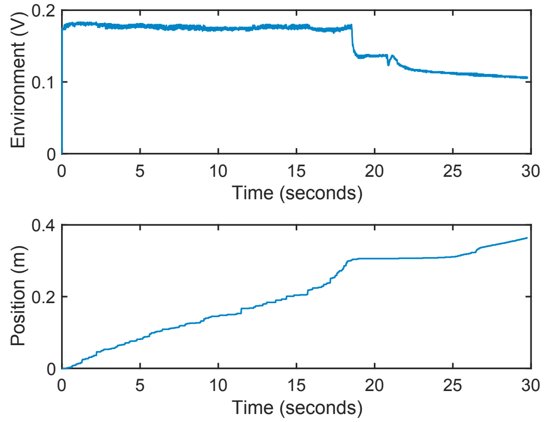

Fig. 7. Environmental assessment of brusque changing context

The second test case is shown in Fig. 7. In this test, it can be seen a brusque change of the environmental variable at 18 seconds. For this case, the context manager decided to halt the robot for 5 seconds at the area, in order to gather more data. This can be seen in the position data being constant in the [18, 23] seconds interval. Afterwards, the robot continues its movement through the fluid.

The plots from both Figs. 6 and 7 show data that was logged by the server. In the *explore* mode, the robot takes its own decisions based on the environmental context of the fluid in which it is submersed.

5. CONCLUSION

The paper presents a context aware cyber-physical system used for submerged environmental assessment. The submersible can operate in both Newtonian and non-Newtonian fluids and can be easily adapted to any monitoring task, limited by CPU performance constraints. The present study shows experimental tests that prove the efficacy of an energy efficient control law as well as the ability of the system to grasp and process its context.

Environmental assessment based on context aware information can be useful in a wide variety of multidisciplinary processes such as under ice exploration (the mixture of water and ice being a non-Newtonian fluid), muddy water monitoring, transportation, biomedical applications such as targeted drug delivery, lung inflammatory response monitoring, anesthesia, etc. or in manufacturing processes that involve both Newtonian and non-Newtonian characteristics such as steel manufacturing, pharmaceuticals (material properties of granulation processes), etc.

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