The Curious Cryogenic Fish - CCF

Christophe Bault,[1] Francesco Becchi,[2] Matteo Cavo,[3] Luigi Iannelli,[4] Giovanna Lehmann Miotto,[1*] Alfonso Madera,[1,4] Francesco Pietropaolo,[1] Xavier Pons,[1] Stephen Pordes,[5] Filippo Resnati,[1]Alberto Traverso[3]

[1]CERN, Espl. des Particules 1, 1217 Meyrin, Switzerland; [2]Danieli telerobot labs, Corso Ferdinando Maria Perrone 47 R 16152 Genova, Italy; [3] TPG-DIME, Università degli Studi di Genova, Via Montallegro 1, 16145 Genova, Italy; [4]Università del Sannio di Benevento, Piazza Roma 21, 82100 Benevento, Italy; [5]Fermilab, Wilson Street and Kirk Road, Batavia IL 60510-5011, United States of America

*Corresponding author: Giovanna.Lehmann@cern.ch

ABSTRACT

The Curious Cryogenic Fish Project aims at developing a robotic device able to perform visual inspections (e.g., detection of bubbles formation, leaks, sparks, etc.) and other environmental measurements inside large cryostats. The idea originates from the particle physics domain, but it has many potential applications, particularly in the field of liquid gas transport and storage, as well as cryogenic plant monitoring.

In this paper the state of the art of the technologies required for the endeavour is summarised, the results of the feasibility studies carried out during 18 months are presented and the necessary future steps to bring the project to maturity are outlined.

Keywords: Cryostat; robotics; motion control, data acquisition

1. INTRODUCTION

The Curious Cryogenic Fish (CCF) is the first device that will be able to thoroughly inspect large cryostats from inside while filled. Remote control of the device will allow for visual inspections and for measurement of environmental data such as pressure and temperature throughout the cryostat volume. In the particular case of cryostats used for Physics experiments, the CCF will be able to generate signals to calibrate the detection devices. A future generation of the CCF may be able to carry out simple repair tasks, exploiting the fast evolution in the field of robotics.
The realisation of the CCF requires not only integration of a set of existing technologies into a device that operates in a cryogenic environment, but also the extension of those technologies to work in this unusual environment.
After first identifying the main challenges for the design of the CCF, the ATTRACT Phase 1 has enabled an initial set of technology studies, with the aim of assessing the feasibility of the project.
In particular:

- commercial cameras have been used to record images inside liquid argon (LAr). This was achieved by keeping the cameras in heated cases, since they do not work at temperatures as low as -186°C. Developing electronics for cameras to work directly at low temperatures requires a long R&D beyond the scope of Phase I;
- wireless data transmission through LAr has been demonstrated: this is a fundamental ingredient, both for collection of data and control of the CCF;
- initial studies of energy storage through batteries have been carried out with promising results: local energy storage is another essential building block, allowing the CCF to move autonomously inside the cryostat without being connected to an external power source;
- exploitation of the properties of a liquid close to boiling point for propulsion has been both simulated and explored through a set of prototypes.

2. STATE OF THE ART

The CCF project merges requirements from two different and apparently distant applications: underwater vehicles and deep space exploration probes. The CCF can be considered an autonomous, remotely operated underwater vehicle; hence the state of the art of remotely operated vehicles applies. The critical environment with extreme temperatures and the high reliability required of the system mean the CCF shares the challenges found in deep space exploration vehicles/probes.

Underwater remote/autonomous vehicles are a mature sector with applications ranging from off-shore operation for maintenance of underwater structures to environmental monitoring and military applications. The global market for remote operated vehicles (ROV) in 2010 [1] was already $850M with $200M for autonomous underwater vehicles (AUV). Underwater ROV [2] range in power and size from the smaller inspection devices of a few kilograms of dry weight and 200-300W of installed power to heavy work-class vehicles of 5000 kg of dry weight and 5 kW of installed power. While extreme depth or harsh environments (as in nuclear fuel pool inspection and cleaning) are aspects of possible ROV applications, the use of ROV in a liquid other than water is something new.
Deep space exploration vehicles require the highest operational reliability. Space applications rely on some key enabling technologies that could be relevant to our project. As an example, the power generation/thermal management of space probes, designed to operate for more than 20 years with no maintenance, could be considered as a potential contribution to our work [3]. Reliability in actuator operation and control as needed in space missions, to avoid, e.g., loss of functionality on a planetary rover robotic arm, is also essential in our case where loss of control of the vehicle inside the cryostat may be fatal for the experiment.

State of the Art References	
Environment (temperature)	deep space (87 K)
Environment (pressure)	shallow water (3 bar)
Dimensions	small ROV (fitting within a sphere of 30 cm diameter)
Power management	underwater/space propulsion
Locomotion	underwater/space propulsion
Lifetime	deep space (>20 years)

3. BREAKTHROUGH CHARACTER OF THE PROJECT

As written in the original project description, the Curious Cryogenic Fish project aims at developing a robotic device for operation in large cryostats "with the ability to perform a full range of visual inspections, integrating the functionalities and performances of a diagnostic station with the flexibility of an unmanned vehicle."
The idea originates from the particle physics domain where projects with thousands and even tens of thousands of tons of LAr are planned. In these projects, complex and delicate devices are immersed in the cryostats, and an interruption that requires intervention inside the cryostat would be extremely damaging in terms of time and money if the cryostat had to be emptied. Our Fish, however, has potential applications in the field of liquefied gas transport, in the monitoring and inspection of cryogenic plants and other areas where large amounts of cryogens are used or stored. Beyond inspection, the Fish may also be used to position or remove calibration or other types of devices (radioactive sources) at arbitrary locations inside the cryostat.
The Breakthrough Character of the project reveals itself in several areas.

- the integration of technologies which already exist standalone but are not yet unified in a single device capable of operating in a cryogenic environment;
- the extension of individual technologies to operate in an unusual, specifically cryogenic, environment;
- the development of a completely novel technique for powering the propulsion of the Fish (a topic not anticipated in the original proposal).

This last area deserves special note. While many of the existing technologies to be used in the CCF are challenged by the cryogenic environment in which they have to operate, this method of propulsion exploits the cryogenic environment to its advantage. The systems being developed have a minimum of moving parts and are based on the observation that the pressure of a volume of cryogenic liquid near its boiling point increases rapidly with the application of a little heat, and that this excess pressure can be used to propel the Fish at minimal expense of power. Exploiting this effect for propulsion is a `first', to our knowledge, and is being developed as a direct consequence of the existence of ATTRACT.

	Technology	Cryogenic Operation	Development Required
Visual Data	HR Camera	Non-standard	YES operation at cryogenic temperatures
Data Transfer and Control	Wi-Fi	Non-standard	YES Must validate transmission through cryogenic medium
Local Power Storage	Li-ion battery	Non-standard	YES Must understand how to operate at cryogenic temperature
Propulsion	Argon Steam or Turbine	Non-standard	Novel – full development

4. PROJECT RESULTS

The main results obtained in Phase I of the project are highlighted here.
The results are grouped into four areas: obtaining visual data, wireless data transmission, energy storage, exploitation of the cryogenic medium phase transition for propulsion.

Visual Data

Our tests showed that commercial cameras typically stop working at temperatures below -40°C, that, however, they survive exposure to -186°C and revive when warmed back to an operating temperature. In order to be able to use cameras for the CCF two options were considered: dissipating energy in order to keep the cameras in a working environment or developing custom electronics to make cameras that work at cryogenic temperatures. The latter approach was considered too ambitious for ATTRACT Phase 1 and the cameras were successfully operated within heated, insulated cases inside LAr. The drawback of this approach is that additional power is consumed in producing the heat.

Wireless communication

Wireless communication is an important ingredient for the CCF, as it will be used both for the transmission of data produced by the onboard devices and for the control of the CCF itself. Successful Wi-Fi transmission was demonstrated via a netcam placed inside a cryostat.

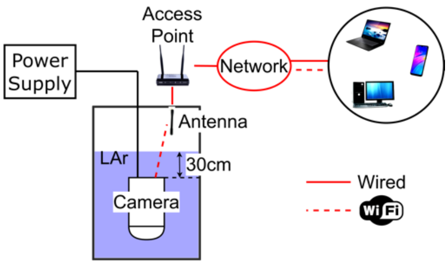

Figure 1 Schematic of the setup demonstrating wireless data transmission.

Energy storage

The ability to store energy [4] is a fundamental aspect of the CCF, since this is what allows the device to operate autonomously. As noted with commercial cameras, batteries stop working at low temperatures. This behaviour, however, is due to the intrinsic nature of the underlying chemical process and is not an issue that can be overcome at present.
The use of Li-Ion cells has been explored and it was demonstrated that these batteries survive in storage conditions at cryogenic temperatures (-186°C). They need to be heated to about -30°C in order to become operational. First tests have produced promising results regarding the lifetime and long-term durability of batteries when operated in such conditions, but more studies are needed. Final results are expected by the end of ATTRACT Phase 1.

Propulsion

The use of electrical motors with propellers is a standard solution that can be used in cryogenic media and has a rich literature on control techniques. During ATTRACT Phase 1 it was decided to study an alternative and innovative propulsion technique, which exploits the cryogenic medium itself.
Cryogenic liquids maintain themselves at a temperature close to their boiling point, and a small rise in temperature is sufficient to produce a significant rise in the pressure of a fixed volume of liquid. Jet propulsion, the propulsion of an object in one direction produced by ejecting a jet of fluid in the opposite direction, exploits this situation and offers an alternative to thrusters (motors) with the advantage of avoiding moving parts which require maintenance.
Two experimental setups have been developed. The first is aimed at validating a single, integrated propulsion unit while the second is designed around a centralized steam generator supplying a network of distributed steam nozzles for propulsion. The first prototype is tested directly in LAr and can serve to validate both simulation results and critical components, such as heater and valves, in the final environment. The second, tested within a Lar simulant (R245fa), develops a more complex architecture with separated boiler and steam over-heater/accumulator.
In the first setup, a compartment of the CCF equipped with two electro-valves is filled with the cryogenic liquid which is heated until the inner pressure reaches a desired value. At that point, one valve is opened, allowing the high-pressure fluid to emerge through a supersonic nozzle and thus generate thrust. The proof-of-concept device assembled to measure the performance of such a system is shown in Figure 2.
Simulations have been performed to determine the optimal size and shape of the nozzle, and to estimate the filling time and maximum achievable distance per cycle. In simulations, the flow evolution and hence the thrust showed unsteady behaviours which may make the control of a jet induced motion difficult.

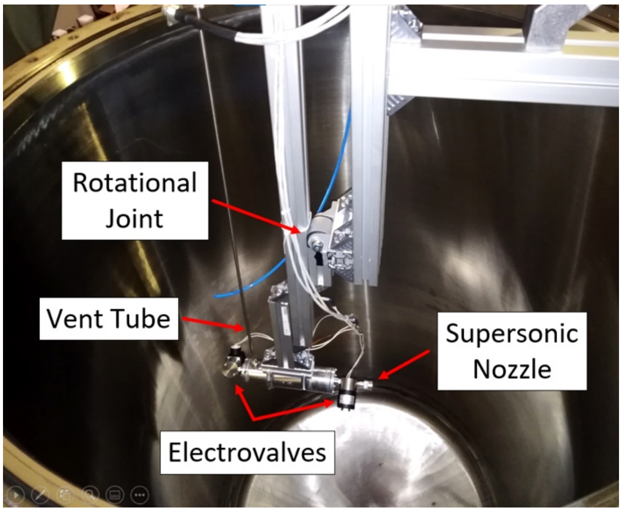

Figure 2: View of the jet propeller prototype, used to measure the generated thrust.

The second prototype draws inspiration from the steam machine concept. The boiler (where the liquid evaporates) and the over-heater (where the steam temperature/pressure are increased) form a centralized unit compatible with the dimensions of the CCF. This device fulfils different functions:

- Pressurized gaseous argon generated in the boiler can be selectively distributed over a set of dedicated supersonic nozzles oriented along the vehicle to control both position and displacement;
- Heat dissipated from the boiler is used to manage the vehicle's internal temperature and maintain batteries and cameras operational.

A functional mock-up (shown in Figure 3) equipped with appropriate instrumentation to monitor temperatures and steam pressure has been built and used to validate both the concept and the first numerical calculations of achievable gas flow and boiler performances. To limit the complexity of the first mock-up, the gas flow is driven only to one supersonic nozzle and components have not been specifically tested for use in cryogenic media. The first test on standard functionalities such as maximum working pressure and thermal tests have been performed with water. Final tests will be performed using a fluid (R245fa) that is a good simulant of LAr, at ambient temperatures.
The collection of experimental data and their analysis will be completed by the end of ATTRACT Phase 1.

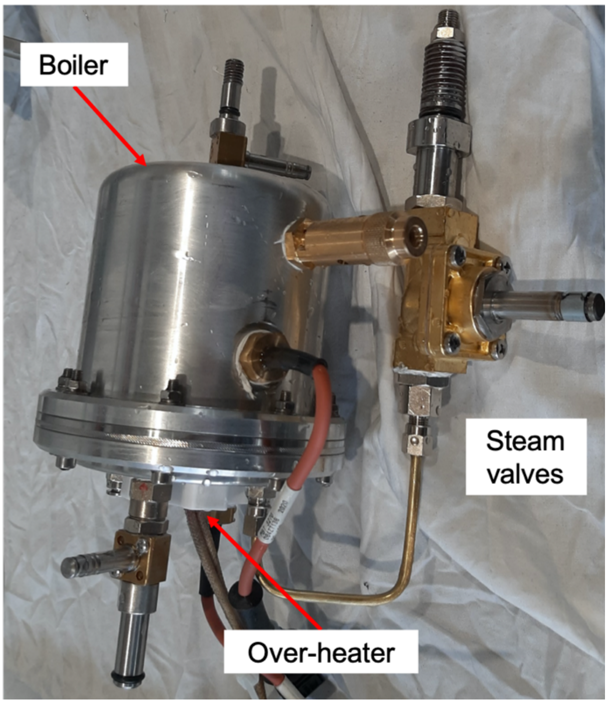

Figure 3: Boiler and over-heater prototype.

5. FUTURE PROJECT VISION

The main goal of the CCF project is to develop a robot suitable to inspect and monitor operational cryostats. As discussed in the project proposal, ATTRACT Phase 1 was oriented to the preliminary investigation of the main technologies, managed according to the different initial TRL, and of the consolidated state of the art in cryogenic engineering or in other similar application fields.

Technology Scaling

The CCF ATTRACT Phase 1 research was structured around two areas:

- Experimental proof of concept of the candidate technologies required for the project;
- Initial investigation of wider perspective technologies that may be potentially useful for the CCF.

In Section 4 we have reported on the main studies done so far on visual data, data transmission, energy storage and propulsion. In addition, the steam machine concept has also been theoretically studied in view of a possible further evolution: if a permanent heat source was embedded info the CCF, the steam may also be used to generate electrical energy for the powering of all the on-board devices.
Experimental tests still need to be completed in order to confirm that there is a valid mechanism for storing energy to allow the CCF to operate without being continuously connected to a power source. Also, the assessment has to be finalised on whether the jet propulsion technique is sufficiently efficient and offers the required fine control of the position and motion of the CCF or whether this development should be abandoned in favour of more conventional thrusters (motors).
The outcomes of the Phase 1 studies, once successfully completed, will allow the structuring of a Phase 2 plan designed along three axes:

- Develop a comprehensive strategy for the control of the CCF, ranging from power management, to measurements control, to safe position and motion control;
- Organize an engineering integration activity starting from the already-validated project "backbones" for a functional cryogenic inspection vehicle to be tested at full scale on a cryostat (TRL6-7);
- Foster the studies on integrated heat source exploitation for longer perspective development.

The first fully integrated prototype would include active thermal management with on-board batteries, controlled positioning and locomotion, an embedded camera transmitting data, and a dedicated charging and docking station. The implementation of this prototype would require 2-3 years with the main focus on thermal design optimization, propulsion control and general integration.

A parallel research activity focused on LAr energy harvesting would be oriented towards a second generation of CCF with its own internal power source and thus a greater degree of autonomy.

Project Synergies and Outreach

The research activity on energy harvesting from LAr in Phase 1 has offered the chance to discuss, with other European research groups, about potential collaborations on CCF Phase 2:

- TPG group from the engineering department of the University of Genova Energy actively joined the CCF research and may be involved as a partner in the future, specifically on thermal machine design, propeller profile optimization and energy harvesting;
- Initial contacts have been made with a professor from the University of Leicester, working on the Radioisotope Thermoelectric Generator (RTG) prototype being developed at ESA, and a collaboration may be established to transfer technology from the ESA programme for a scaled power version of their RTG for a CCF with advanced thermal management.

Technology application and demonstration cases

The CCF prototype foreseen at the end of Phase 2 will already allow inspection of an operational cryostat, with limited mission duration and possibly a safe-line for recovery in case of failure. The first show case could be the insertion of the CCF inside one of the large cryostats used by the Neutrino Platform at CERN [5].

Technology commercialization

For the full duration of Phase 1 the stake holders of the first direct application of the CCF were actively involved, to ensure that the project development was coherent with the requirements of the ultimate application. A wider exploitation of the CCF could be considered, outside the research field, for other emerging applications of cryogenic storage (eg. Cryohub.eu,) or the liquid gas transport and storage: a structured assessment of the potential market in this direction is foreseen in the course of ATTRACT Phase 2.

Envisioned risks

As Phase 1 has already covered the validation of the principal CCF project "building blocks" the main risks in Phase 2 will be related to the system safety and control, the integration and system engineering: particular attention will be dedicated to meeting dimensional and operational requirements. Prototype dimensions, locomotion and its control, thermal management power requirement, and the battery capacity are all inter-related: the dimension constraints may have an impact on the achievable duration of inspection missions.
Furthermore, the requirements on safety, in particular in case of CCF failures, may be challenging to be fully met already in Phase 2.

Liaison with Student Teams and Socio-Economic Study

ATTRACT Phase 1 has already been the subject of a Master thesis and of a PhD thesis. The project will continue offering numerous challenges in the fields of robotics and automation, mechanical and electronics engineering, which makes it well suited for training of students and for fostering innovation through university collaborations. There is an ongoing collaboration with two Italian universities and in ATTRACT Phase 2 we plan to further enlarge the academic links.
The CCF in Phase 2 may be an interesting use-case for a team of students to contribute to setting up an initial business and marketing plan beyond the research environment.

6. ACKNOWLEDGEMENTS

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