

FlatFish – A compact subsea-resident inspection AUV

Jan Albiez^{*†}, Sylvain Joyeux^{*}, Christopher Gaudig[†], Jens Hilljegerdes[‡], Sven Kroffke[‡], Christian Schoo[†], Sascha Arnold[†], Geovane Mimoso^{*}, Pedro Alcantara^{*}, Rafael Saback^{*}, Joao Britto^{*}, Diego Cesar^{*}, Gustavo Neves^{*}, Thomio Watanabe^{*}, Patrick Merz Paranhos^{*†}, Marco Reis^{*}, and Frank Kirchner^{†‡*}

^{*}Brazilian Institute of Robotics, SENAI CIMATEC, Salvador, Bahia, Brazil, Email: jan.albiez@fieb.org.br

[†]Robotics Innovation Center, DFKI GmbH, Bremen, Germany

[‡]Robotics Group, Universität Bremen, Bremen, Germany

Abstract—Currently the inspection of industrial underwater structures is performed by remotely operated vehicles or by divers. Since the number of underwater structures keeps growing, e.g. due to new oil and gas fields or offshore wind farms, the need for a constantly available method to inspect these structures arises. The FlatFish project is an initiative of BG Group Brazil and the Brazilian Institute of Robotics in Salvador and aims at developing a subsea-resident AUV which can inspect the infrastructure at an oil and gas site on demand. FlatFish is a compact AUV, designed to acquire a high-resolution, textured 3D model of an underwater structure within an oil and gas asset. FlatFish is very agile and can hover during inspection, it uses a novel kind of navigation system to safely reach its goal within the field and is designed to stay submerged for extended periods of time. Within this paper the system design of FlatFish is presented.

I. INTRODUCTION

Underwater structures like oil and gas production systems or the foundations of buildings, piers and off-shore wind facilities, have to be regularly inspected to evaluate the state of the structure and to plan future interventions for repair and maintenance. These inspections are currently performed by remotely operated vehicles (ROVs) or, if water depth and availability allow it, by divers. Due to the fact that inspections of this kind require a special support vessel, they are time-consuming, expensive, need to be planned a long time in advance and rely on good weather conditions and seasonal constraints (e.g. not during hurricane season or winter storms).

Especially when looking at subsea operations of the oil and gas industry, being able to inspect the subsea part of an asset regularly and/or on demand plays a key role for subsea asset integrity assurance (SIA) and integrity management. The key information gathered from inspections encompasses the general structural integrity and close visual data (also known as close visual inspection, CVI). The former can be acquired by using sonars from a greater distance. For the latter, a camera has to be brought close to the structure. Being able to retrieve information on the current state of any subsea equipment within the field whenever the need for an assessment arises, allows for much safer operations and a reduction of the operational expenditures (OPEX) due to the ability to better plan asset maintenance. While this already holds true for current offshore assets, it becomes crucial for the planned deep sea assets or in future fields with more complex seafloor production systems.

These kinds of inspections are logistically and financially not feasible with ROVs since that would require the continuous presence of an ROV support vessel in the field. There are very few installations with ROVs deployed from FPSOs, but the tether length limits the operational radius to an area around the FPSO. The solution is the usage of autonomous underwater vehicles (AUVs) for in-field inspection. [1] already predicted the increase of AUV capabilities and their use in tasks beyond classic bathymetry.

AUV systems suitable for delivering the desired inspection data require enhanced capabilities. The robot must be able to position its cameras and lights close to the inspection target without damaging the structure. This requires an ROV-like maneuverability combined with a control system maintaining safe operations. This hovering ability is one of the key capabilities which is commonly used to distinguish bathymetry-class AUVs from inspection-class AUVs.

To guarantee that at any given time an inspection of the asset's subsea structures can be performed, the AUV has to be readily available 24/7. Since deck space on platforms and FPSOs is generally tight and to reduce the influence of the weather on operations, the solution is to operate the AUV in a *subsea-resident* mode. Within the AUV context, subsea-residency means that the robot has a dedicated docking station on the seafloor within the asset. This docking station is connected to the topside facilities of the asset. While docked, the AUV can be charged, data can be downloaded from the AUV and mission information can be uploaded to the AUV. When an inspection is required, the mission is created on shore or topside and transmitted to the AUV. The AUV then leaves the docking station, executes the mission and returns to the docking station to recharge the batteries and transfer the inspection data.

Subsea-residency is not a new concept. The idea has already been appearing in research and development for some time (e.g. [2]). But until now the technology for actually implementing a subsea-resident vehicle was not available. Subsea-residency originated from oceanographic research, where its intended use was to expand the ranges of long-term environmental monitoring. Worldwide there are a few projects ongoing which plan to use resident AUVs in the mid- to long-term, e.g. [3] or [4].

The requirements for a subsea-resident AUV and its support infrastructure are high. All components have to be robust

enough to be able to function even when being exposed to the deep sea environment for extended periods. This includes corrosion, bio-fouling, degradation of seals and the blockage of moving parts like thrusters and locking mechanisms by sediments or other foreign objects. The AUV as well as the infrastructure have to be designed in a way that on one hand addresses the aforementioned problems and on the other hand allows for quick and cost efficient maintenance.

A. Project FlatFish

The FlatFish project is an initiative between BG Group Brazil and the Brazilian Institute of Robotics (BIR) in Salvador and is funded through the Brazilian Government R&D levy, which requires 1% of gross production revenue from large Brazilian oil and gas fields to be invested in R&D in Brazil.

FlatFish aims to develop a subsea-resident inspection AUV. The project is part of a long-term research roadmap of BG Group Brazil in the area of robotics for oil and gas production. The development of the AUV is divided into two phases: In the first phase the development infrastructure in Brazil will be set up, the AUV will be designed and integrated, and the first inspection tests will be conducted inshore off the coast of Salvador, Brazil and in the maritime test tank at DFKI in Bremen, Germany. The second phase will focus on extended offshore trials of the complete system, including the docking station, within an asset of BG Group. Currently the project is at the end of the first phase.

During a workshop between BG Group, BIR and DFKI at the beginning of the FlatFish project, the scenario and the principal design parameters were defined. The scenario was defined as follows:

- 1) The AUV resides within a docking station on the seafloor
- 2) Topside sends a mission to inspect a specific structure within the asset, e.g. a manifold or an SSIV
- 3) FlatFish leaves the docking station and navigates toward the specified structure using pipelines and other subsea structures as external references
- 4) While in transit, FlatFish uses its onboard sensors to avoid obstacles and to record data of the asset's status (e.g. pipelines or debris)
- 5) At the inspection target, FlatFish uses an advanced camera system to perform a close visual inspection of the complete structure
- 6) FlatFish returns to the docking station using the same navigation approach as before
- 7) In the docking station the batteries are recharged, the data is downloaded to a topside server and a high-resolution video-linked 3D model is created as the inspection result.

With this in mind, the basic requirements for the FlatFish AUV were set to the following:

- Compact design with hovering capabilities
- Materials and mechanical design that allow for a long-term subsea deployment
- Extended sensor suite for highly detailed visual inspection

TABLE I. FLATFISH – TECHNICAL DATA

Depth rating	300 m
Weight (in air)	275 kg
Size (LWH)	220 cm x 105 cm x 50 cm
Propulsion	6x 60N Enitech ring thrusters (120N in each direction)
Battery	Lithium-Ion battery 5,8 kWh (11,6 kWh) @ 48V
Communication (surface)	Rock7mobile RockBlock Iridium satellite modem (1,6 GHz) Digi XBee-Pro-868 (868 MHz) ubiquiti PicoStation M2 HP WLAN-Modul (2,4 GHz)
Communication (submerged)	Evologics S2CR 48/78 kHz usable as USBL transponder
Communication (tethered)	10 GBit/s optical fibre 1 GBit/s Cat5e (max. 50m)
Light	4x Bowtech LED-K-3200 (3200 lumen each)
Laser Line projector	2x Picotronic LD532-20-3(20x80)45-PL line laser 20mW each @ 532nm
Sonar	BlueView MB1350-45 Multibeam Profiler (inspection sonar) Tritech Gemini 720i Multibeam Imager (navigation sonar) 2x Triton Micron Sonar (obstacle avoidance)
Camera	4x Basler ace acA2040-gc25 2048x2048 at 25 frames/s, colour, GigabitEthernet
Depthsensor	Paroscientific 8CDP700-I
INS/AHRS	KVH 1750 IMU
DVL	Rowe SeaProfilor DualFrequency 300/1200 kHz

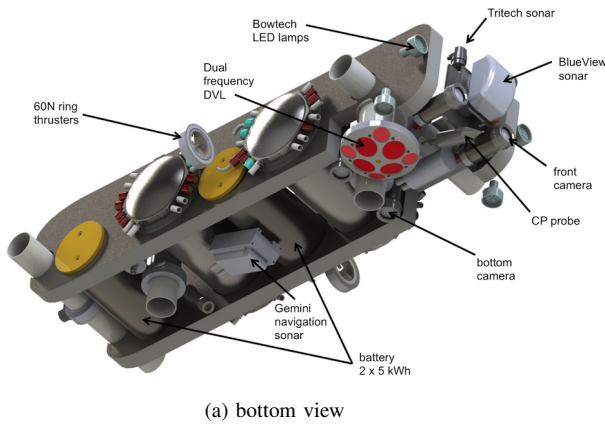
- Multi-modal navigation system tailored to use the asset's structure as landmarks
- Multiple tracking systems, e.g. pipeline tracking, cable tracking, structure tracking
- Online 3D reconstruction for adaptive inspection coverage and offline dense 3D reconstruction with referencing between video data and 3D model

This paper focuses on the FlatFish AUV. The developments within the project are shown in regard to the current state-of-the-art for inspection-class AUVs and the design of the AUV is presented.

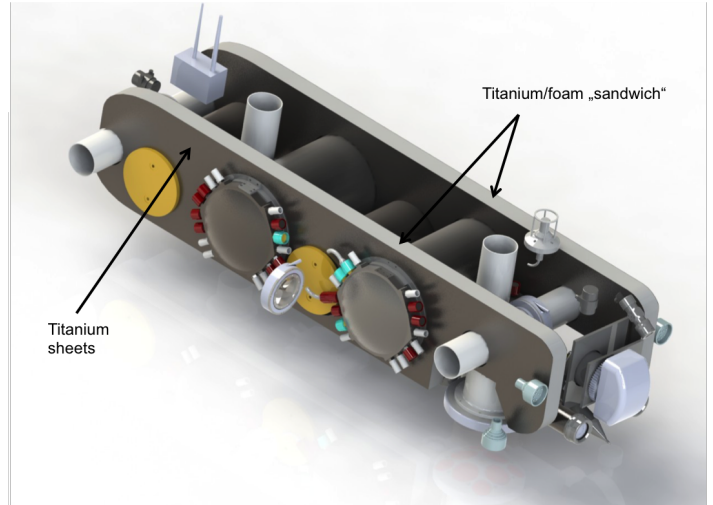
II. INSPECTION-CLASS AUVS

The primary task for autonomous underwater vehicles has always been data collection. Initially, AUVs were designed to enhance the quality of sonar-based wide area surveys by operating closer to the ground than a surface vessel and without the influence of waves. Up to this day facilitating high-resolution bathymetric maps is still the primary application for AUVs. Other wide area operations are the search for objects such as flight recorders (see [5]) or mine hunting (see [6]). AUVs designed to perform this kind of tasks commonly use one propeller and control planes and therefore lack the ability to *hover*, meaning that they can't keep their position like ROVs. The ability to hover is a key requirement to perform inspection tasks on complex structures. Therefore this ability distinguishes inspection-class AUVs from mapping systems.

In recent years several AUV manufacturers developed prototypical modifications to their mapping AUVs to perform inspection tasks, e.g. the modified REMUS 500 presented in [7]. All of these modifications have in common that hovering is relatively expensive regarding energy consumption, so



(a) bottom view



(b) top view

Fig. 1. Placement of FlatFish's components (sensors, thrusters etc.)

inspections which mainly rely on ROV-like motions are not feasible with these systems.

SubSea 7's autonomous inspection vehicle (AIV) [8] comes close to the requirements defined for the FlatFish project. Nevertheless, the AIV mainly operates based on sonar, keeps longer distances to the inspection target and lacks the required high-resolution video system.

Lockheed Martin's Marlin [9] is a large AUV primarily designed to carry a bulky 3D imaging sonar. It has been used to perform optical surveys as well (see [10]) but with mixed results. There have been some attempts to use the Saab Seaeye Sabertooth [11] as an inspection-class AUV, but it suffers from the same size-related problems as the Marlin.

There are several prototypes and single systems used in robotic or marine research. Examples are the Italian TriMares [12] used to evaluate dam inspection by AUVs, the Spanish Girona 500 vehicle [13] used in different European projects and the Sentry AUV of the Woods Hole Oceanographic Institution in the USA, best known for its work during the Deepwater Horizon accident [14]. All these systems have in common that they are unique solutions with special research interests.

A special case currently under development are so-called *hybrid* ROVs, which are hovering AUVs that are remotely controlled via a thin optical fiber during the inspection/scientific part of their mission. The first known vehicle of this kind was the deep-diving NEREUS [15]. An example for a recent system is the HROV [16] of the German MARUM.

The development in FlatFish is based on the work of the DFKI RIC on the design of inspection AUVs. It mainly builds upon the operational experience with DAGON [17] and on the mechatronic system of LENG [18].

III. BRAZILIAN-GERMAN DEVELOPMENT

FlatFish is developed in a joint effort between the Robotics Innovation Center (RIC) of DFKI in Bremen, Germany and

the Brazilian Institute of Robotics (BIR) in Salvador, Brazil. This cooperation creates the unique opportunity to combine the indoor testing facilities and the experience with autonomous underwater robots in Bremen and the extensive testing opportunities and the emerging commercial and scientific market in Brazil.

The key elements of this cooperation within the project are the testing facilities which complement each other, the joint development of hardware and software and the training of researchers and other personnel.

The centerpiece of the maritime exploration hall¹ at the facilities of DFKI RIC in Bremen is a 3.5 million liter saltwater test tank. This tank allows for comprehensive tests of systems and control algorithms in a completely controlled and safe environment. It is large enough for FlatFish to operate freely.

The coastal waters around Salvador have an average depth of approximately 30m and offer a variety of different testing environments, close to offshore conditions with respect to visibility and currents. The weather allows for nearly year-round testing with only a short time in autumn (May to mid July) where high waves and thunderstorms can limit the ability to test.

Both locations will have their own FlatFish AUV. The first is being built in Bremen, the second will be integrated in Salvador. Having two identical vehicles allows a seamless test, evaluation and improvement of algorithms, hardware and operational procedures. E.g., a new algorithm for sensor processing can be tested in the clear water environment at the Bremen site and its principal functionality can be verified before it is tested in the ocean environment in Salvador. The results of the tests in Salvador can then be analyzed at both locations, any problems can be identified and the testing cycle can start again. With both locations working in parallel this cycle can be very quick and efficient.

¹<http://robotik.dfk-bremen.de/en/research/research-facilities/maritime-exploration-hall.html>

Working in a transcontinental cooperation forced the team to establish modern methods of distributed development, change management, issue tracking, document management and communication. The primary tool for coordinating the development work is github² which already brings all the tools needed to manage a distributed team of software developers. In addition to github a build-server is used to verify the current state of the software integration and runrun.it³ is used to manage the tasks of the team members and to coordinate the work between them.

IV. THE FLATFISH AUV

A. Mechatronic Design

The main goal of the FlatFish design was integrating all necessary sensors, the thrusters, the battery system and the electronics into a compact system. Early in the design phase the decision was made to use an open-frame design since it allows more freedom in placing components and sensors. Figure 1 shows the CAD model of the AUV without the cover to illustrate the placement of the components. The inspection sensors are described in section IV-E, the navigation system is the topic of section IV-D, all other components are described in more detail now.

a) Frame, Support and Cover: The frame features a titanium sheet buoyancy foam composite and the launch and recovery hook support consists of welded titanium. This design allows for a very lightweight but still robust structure. The cover is made from fiberglass and its primary function is to reduce the potential points of entanglement while its secondary function is to reduce the hydrodynamic drag.

b) Pressure Housings: An analysis of the volume occupied by the electronics and the batteries showed that distributing the dry electronics into multiple smaller titanium pressure housings would reduce the size and weight of the housings. For reasons of modularity and weight distribution within the system, the batteries are placed in two pressure housings while the PCs, power electronics etc. are distributed in two separate housings. The caps of the pressure housings are easy accessible from the side of the vehicle, thus facilitating maintenance.

c) Propulsion System: FlatFish is propelled by six hubless, pressure neutral ring thrusters. This type of thrusters is very robust with respect to extended underwater use and is able to withstand most kinds of debris without being blocked. The thrusters are configured in a rectangular configuration with two for each of the primary directions surge, heave and sway. This configuration is less agile than the ROV-type vectored thrust but much more efficient since full thrust is given in the desired direction of motion.

d) Communication System: FlatFish is equipped with a wide range of communication channels. All surface communication systems are gathered in a communications tower at the rear of the AUV which rises out of the water when FlatFish is surfaced. The comms tower is equipped with an Iridium satellite modem for worldwide communication, a GPS receiver, a 2.4GHz wireless LAN access point, an XBee Pro modem

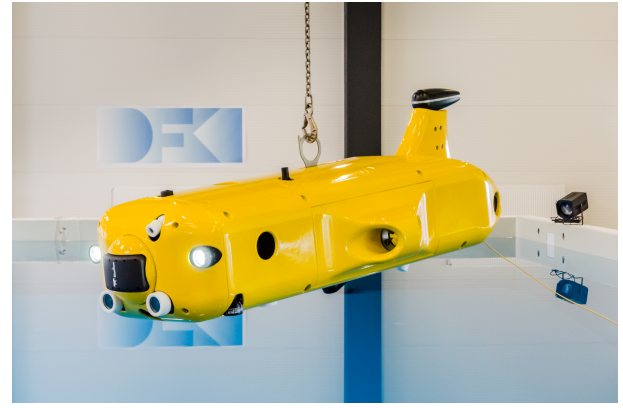


Fig. 2. The completely integrated FlatFish at the DFKI RIC test facilities in Bremen, Germany.

for redundancy and safety and a high-power LED beacon. For communication when submerged FlatFish is equipped with an acoustic modem. The comms tower can be configured to automatically transmit its GPS position via Iridium when it has satellite contact and it is equipped with its own backup battery.

It is possible to equip FlatFish with a short (100m) copper tether or a long fibre-optic cable turning it into a hybrid ROV. While this feature is not needed in the final application scenario it is a significant advantage during development.

e) System Management: All electrical components are connected to the power supply via electronic fuses, which are controlled by the system management board. The system management board is the part of FlatFish which controls the power to all other components in the system. It is the first component which powers up after a system start and the last component which switches off. The system management is directly connected to the XBee communication, acts as proxy for the underwater communication and controls the access to the propulsion system. The system management board itself is equipped with a watchdog and a brown-out circuit. Via the system management the AUV can activate, de-activate or reboot every component of FlatFish. The only exception being the battery-powered comms tower.

This setup is the basis for a robust and fault-tolerant system, which is a necessity for long-term deployment. Every component of the AUV can be switched off in case of a major fault or be rebooted for fault recovery. Since the system management regulates access to the thrusters and can be contacted via every communication channel, the AUV can be forced to surface even when the main control software is malfunctioning. Also, FlatFish can be directly controlled at the surface via WiFi or XBee.

f) Computer System: FlatFish is equipped with two computers. One is the dedicated control PC which runs the low-level control, the navigation system and the mission management. The second PC is the payload system, and therefore is the host of the inspection software. The PCs are connected via Gigabit Ethernet which also acts as the main communication backbone.

Figure 2 shows the fully integrated system at the DFKI

²<https://github.com/>

³<https://runrun.it/>

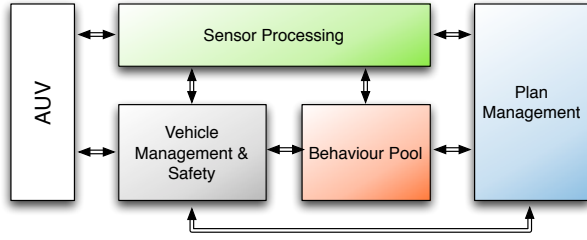


Fig. 3. High-level view of the FlatFish control architecture

facilities in Bremen.

B. Software Architecture

The vehicle’s software architecture is based on the Robot Construction Kit (Rock⁴), a component-based software integration framework for robotics. The work done to use Rock on FlatFish is a continuation of previous work, to which some of the authors contributed, on other AUVs [19] and H-ROVs [20].

From the point of view of vehicle development, Rock provides the common set of tools and services that is nowadays considered standard: visualization, logging (storing data), log replay (passing logged data to live components for testing) and state monitoring. Where Rock differentiates itself is in its focus on robustness.

Rock’s architecture design supports the integration and *coordination* of software components that have a single purpose [21], that is have a well-defined function that is as stateless as possible. This contrasts with the common approach of “fat components”, whose behaviour very often depends on a lot of internal states, and is therefore hard to assess externally. The components in the FlatFish architecture are meant to be designed for a single purpose, which makes external diagnostic easier, and allows to make them *fail early*. The handling of these faults is then delegated to the system’s coordination layer, Syskit[22].

Syskit is a model-based approach designed to handle a component-based approach to data processing in the robotic context 3. In addition to its diagnostic and fault recovery aspects, it allows to design the different configurations of the system’s component networks, building a *Behaviour Pool*, and then combine them in more complex systems (correct-by-construction). At runtime, these various subsystems can then be switched on or off when needed by the *Plan Manager*, while leaving the details of which parts of the software should be shut down or brought up to the model-based approach. This allows to very easily provide hybrid ROV/AUV functionality, where any AUV functionality can be enabled or disabled by a ROV operator when needed, including fully autonomous mission modes.

Given Syskit’s complexity, the software architecture includes *Vehicle Management and Safety* functionality. This functionality, separated from the Syskit-based blocks, has low autonomy. Its goal is to verify properties that are critical to the underwater asset’s integrity as well as the vehicle safety (the former having higher priority than the latter). It can take over

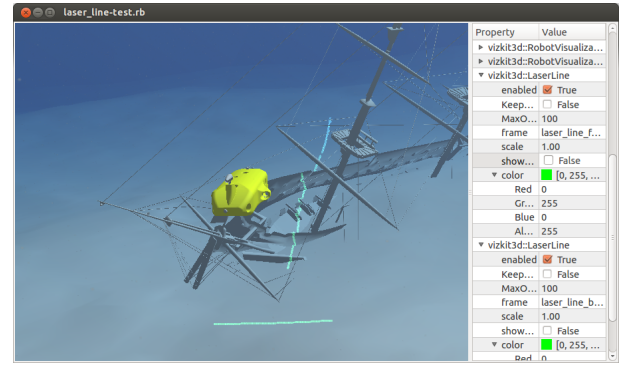


Fig. 4. Screenshot of the simulation with an active FlatFish using the laser line projectors.

vehicle control to enter a safe mode when needed, completely bypassing Syskit’s own functions.

C. Simulation

In order to test the software integration and the mission and fault handling behaviours, we have integrated the Gazebo realtime simulator⁵ into Rock.

Out of the box, Gazebo does not provide all the functionality required for FlatFish, namely the following missing components:

- water effect simulation for cameras, in particular the loss of color and the limited depth of view,
- physical effects of water (buoyancy, drag and added mass),
- simulation of different sonar types,
- the Rock integration

Our work consists firstly of a clean integration of Gazebo into the Rock framework, and secondly its extension to support the simulation of an underwater environment. Technical details about this integration can be found in [23].

D. Navigation System

One of the largest problems for AUVs is a precise localization while en-route. Contrary to ROVs, an AUV normally has no base vessel which can localize it acoustically. An AUV solely has to rely on its INS and the DVL used with dead-reckoning to compute the current position and therefore accumulates an error over time. This error grows larger the more the AUV turns, a typical motion when performing an inspection. During some AUV missions a large baseline (LBL) transponder net is deployed to correct for errors (e.g. [5]), but setting up a LBL network is a major logistical effort.

The navigation system of FlatFish makes use of the installations and infrastructure within an offshore asset to guarantee safely reaching an inspection target, even if this target is located a long distance away from the docking station. Since every part of the asset is in some way connected to the platform or the FPSO, FlatFish uses these connections,

⁴<http://rock-robotics.org/>

⁵<http://gazebo-sim.org>

normally pipelines or umbilicals, as navigation aids. Instead of an absolute global localization, FlatFish uses pipelines and umbilicals like roads connecting the individual parts of the asset. FlatFish metaphorically carries a map of the asset and uses it for navigation. This layout-aided navigation uses several modalities which are fused whenever they are applicable (see also figure 5):

INS/DVL: The fusion of the INS, the DVL and the vehicle's motion model into a dead-reckoning system by using an Extended Kalman Filter (EKF)

USBL: Within a 1km range from the docking station, the USBL/modem is used to help FlatFish find its dock. Current plans only have the docking station equipped with an USBL, but it is also possible to equip other parts of the asset (like manifolds) with a USBL repeater to further aid navigation.

Pipelines & Umbilicals: FlatFish possesses an advanced opto-acoustic pipeline and cable tracker. Using this tracking system, FlatFish can *lock* onto the pipeline connecting its current inspection target with the rest of the asset and safely find it, even if the target is several kilometers away from the docking station. A further benefit of this tracking is, that a general visual inspection of the pipelines within the asset is done automatically.

Acoustic Feature Detection: It is planned to use the forward-looking imaging sonar (Tritech Gemini 720i) to support the transition between the junction at the end of the pipelines/umbilicals and the current target of the navigation.

3D reconstruction/inspection: The main part of the inspection data processing is done offline (see section IV-E), but the coverage check is done by an online algorithm. This part of the inspection system is used to localize the AUV with respect to the inspection target. This is of special importance since it is expected that the DVL will produce errors due to the close proximity to the structure, thus leaving the dead-reckoning in a critical state.

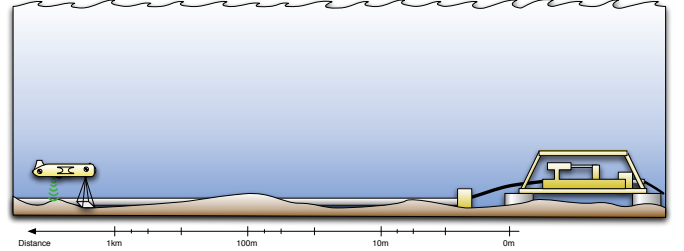
The fusion of all these modalities into the final localization solution will be done by an EKF.

E. Inspection System

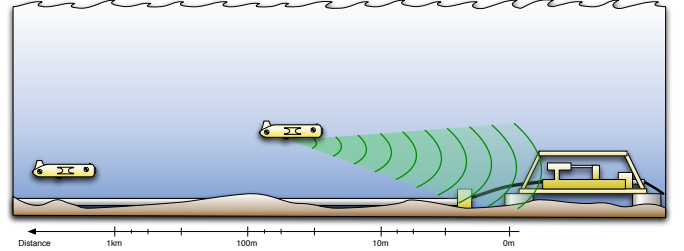
The inspection system is the key element of FlatFish. To fulfill the requirements regarding inspection data, a multi-modal approach was chosen. The idea behind this is to decrease the influence of the environmental conditions, mainly visibility, on the gathering of inspection data as much as possible.

The inspection sensor system consists of three sensor modalities, two optical and one acoustical:

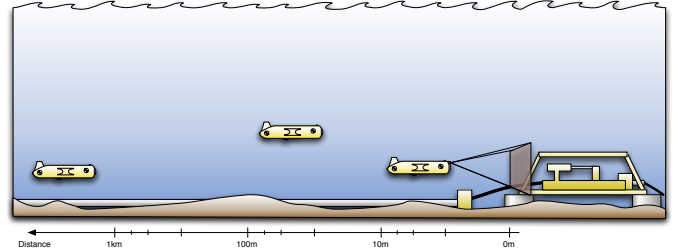
Profiling Multi-Beam Sonar: To allow a general inspection from greater distances or in very high turbidities (bad visibility), FlatFish is equipped with a high-resolution multi-beam profiling sonar (Blueview MB-1350). This sensor is mounted at the front of the AUV and can be turned by an electric rotator to change the orientation of the sonar fan between horizontal and vertical. By tracking the vehicle motion, the profiling sonar is used to generate a 3D model of the target structure in bad visibility and will be used as an additional modality for the visual inspection.



(a) During transitions the INS/DVL-based localization is supported by tracking of asset structures like flowlines



(b) Closer (less than 100 m) to major asset structures the forward-looking imaging sonar and the obstacle avoidance sonar are used to localize the structure



(c) During inspection the 3D reconstruction data (visual and sonar) is used to track the AUV's relative position with respect to the structure

Fig. 5. Overview of the three major navigation modalities for the layout-aided navigation of FlatFish

Stereo Camera Systems: FlatFish is equipped with two stereo camera systems. One forward-looking system and one downward-looking system also mounted in the front half of the AUV. Both systems use the same 2k Ethernet cameras (see table I) which are directly connected to the inspection PC. The camera systems are supplemented by a set of dimmable lamps each. The system is expected to work in conditions where the visibility range exceeds 2m. For higher turbidities the data acquired does not provide the quality required for the inspection. The stereo cameras are used in conjunction with a structure-for-motion algorithm to generate a high-resolution, textured 3D model of the structure to be inspected.

Laser Line Projection: FlatFish features two green laser line projectors (20mW@532nm) which can be switched on by software and project a laser line onto the image of each of the stereo cameras (see figure 6). With the help of an automatic extraction system (see [24]) and by tracking the motion of AUV, the laser line is used to generate a 3D model of the inspection target (e.g. like in [10]). The advantage of the laser line projector is, that it works even in high turbidities (see [25]). But even under good visibility conditions it can support the stereo system by providing exact distances to a target.

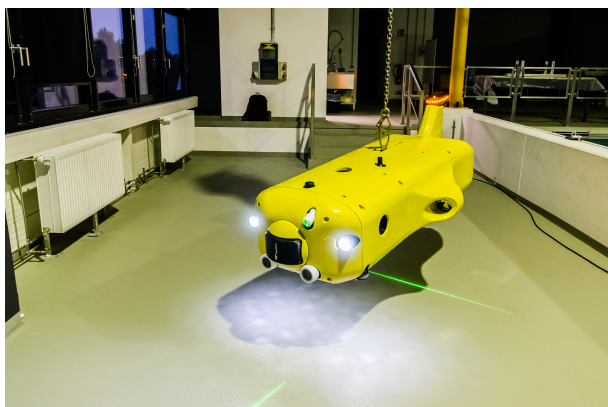


Fig. 6. FlatFish attached to the crane at DFKI in Bremen. The green lines of the laser projectors under and in front of the AUV can be seen. On the front of the AUV the BlueView inspection sonar, the lights and the forward-looking stereo camera system is visible.

The inspection itself is pre-planned by using either the CAD model of the structure or a model from a previous run. While inspecting, an online model is generated which is used for navigation and for verifying the coverage of the structure. After the return of the AUV to the docking station and the transfer of the data to topside, this model is used as the basis for generating the high-resolution inspection model. This inspection model is linked to all the raw data used to generate it (e.g. videos) and allows the operators of the asset to do a structure-based browsing of the inspection results.

V. INTEGRATION TESTS

In June 2015 the integration of the first vehicle was finished in Bremen, Germany and a series of specification compliance tests was performed by BIR scientists together with the staff at DFKI. The goal of these tests was to check whether the fully integrated AUV complies with the specifications regarding the mechatronic system and the basic motion capabilities.

The tests were performed in the large saltwater tank of the maritime exploration hall in Bremen. A mock-up of a pipeline was installed as a visual target for the vehicle and the experiments were documented using a Mini-ROV (see figure 7).

The tests consisted of a series of tracks which FlatFish had to follow using the INS/DVL-based dead-reckoning pose estimator and the waypoint-following behaviour. The pipeline mock-up was the target for testing the downward-looking camera system and was used as a test object for the pipeline detector. The FlatFish AUV was able to successfully fulfill all parts of the test. The waypoint navigation autonomously followed a set of waypoints in the tank over a time period of 30 minutes. All sensors of FlatFish worked correctly and the pipeline detector was able to detect the pipeline whenever FlatFish crossed it.

VI. CONCLUSION

The FlatFish AUV is the first step towards an integrated subsea-resident inspection system for offshore oil and gas. The design and testing philosophy using a multinational team

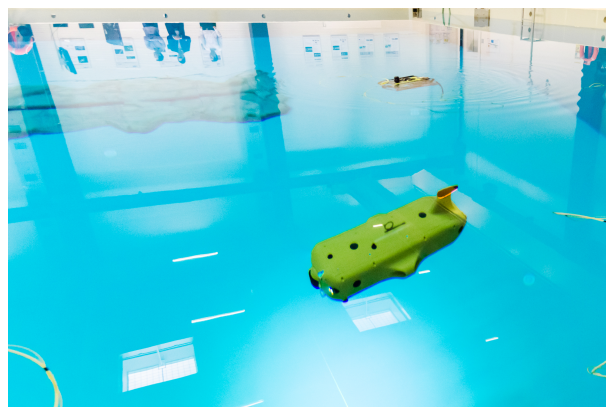


Fig. 7. FlatFish in the maritime test tank at the DFKI facilities in Bremen during the specification compliance tests. The pipeline mock-up is visible in the top left of the picture.

was presented, the mechatronic design introduced and the navigation and inspection systems outlined.

The specification compliance tests done at the DFKI RIC in Bremen, Germany showed that the mechatronic design of FlatFish is in accordance to the specification. The next step in the project consists of extensive tests inshore off the coast of Salvador with the Brazilian FlatFish. As inspection target one of the various shipwrecks in the Bahian waters will be chosen, since the process to qualify FlatFish to work in an offshore asset is still ongoing.

In parallel, the design and integration of the docking station prototype will be done. The tests of the docking process will primarily be performed in the clear saltwater tank in Bremen.

Future work on FlatFish will focus on qualification of FlatFish for offshore assets, enhancing the inspection capabilities, performing field trials in an offshore oil and gas asset and enhancing the navigation system by incorporating new methods like magnetic tracking [26] and increasing the level of autonomy.

ACKNOWLEDGMENT

The FlatFish project is part of the ongoing research and development program of BG Group Brasil. It is funded by the Brazilian government via the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) and, due to its high innovative nature, co-funded by the EMPRAP II (Empresa Brasileira de Pesquisa e Inovação Industrial) program.

The authors would like to thank BG Group for the excellent support of the project, with special thanks to Gordon Laurenson, Phil Bremner, Diana Charles, Andrew Brown, Dawood Moataz, Steve Miller, Rosane Zagatti and John Costin.

REFERENCES

- [1] Douglas-Westwood, *AUV Gamechanger Report 2008-2017*. Douglas-Westwood, September 2007.
- [2] D. Mcleod and J. R. Jacobson, "The role of autonomous underwater vehicles in deepwater life of field integrity management," in *Proceedings of the Offshore Technology Conference (OTC) Brasil*. Rio de Janeiro, Brasil: Offshore Technology Conference, 2011, pp. 1–6.

- [3] C. German, M. Jakuba, J. Kinsey, J. Partan, S. Suman, A. Belani, and D. Yoerger, "A long term vision for long-range ship-free deep ocean operations: Persistent presence through coordination of autonomous surface vehicles and autonomous underwater vehicles," in *IEEE/OES Workshop on Autonomous Underwater Vehicles AUV 2012*, Southampton, UK, Sept 2012, pp. 1–7.
- [4] T. Soltwedel, U. Schauer, O. Boebel, E.-M. Nothig, A. Bracher, K. Metfies, I. Schewe, A. Boetius, and M. Klages, "FRAM - frontiers in arctic marine monitoring visions for permanent observations in a gateway to the arctic ocean," in *Proceedings of the IEEE/MTS OCEANS 2013*, Bergen, Norway, June 2013, pp. 1–7.
- [5] M. Purcell, D. Gallo, G. Packard, M. Dennett, M. Rothenbeck, A. Sherrill, and S. Pascaud, "Use of remus 6000 auvs in the search for the air france flight 447," in *OCEANS 2011*, Sept 2011, pp. 1–7.
- [6] M. Couillard, J. Fawcett, and M. Davison, "Optimizing constrained search patterns for remote mine-hunting vehicles," *IEEE Journal of Oceanic Engineering*, vol. 37, no. 1, pp. 75–84, Jan 2012.
- [7] G. Packard, R. Stokely, R. Christenson, F. Jaffre, M. Purcell, and R. Littlefield, "Hull inspection and confined area search capabilities of remus autonomous underwater vehicle," in *Proceedings of the IEEE/MTS OCEANS 2010*, Sept 2010, pp. 1–4.
- [8] Subsea7. (2015, February) Autonomous inspection vehicle – aiv. [Online]. Available: <http://auvac.org/uploads/configuration-spec-sheets/AIV.pdf>
- [9] Lockheed. (2015, March) Marlin mk1 spec sheet. [Online]. Available: <http://auvac.org/uploads/configuration-spec-sheets/MARLIN.pdf>
- [10] D. McLeod, J. Jacobson, M. Hardy, and C. Embry, "Autonomous inspection using an underwater 3D LiDAR," in *Proceedings of the IEEE/MTS OCEANS 2013*, San Diego, USA, Sept 2013, pp. 1–8.
- [11] B. Johansson, J. Siesjö, and M. Furuholmen, "Seaeye sabertooth a hybrid auv/rov offshore system," in *Proceedings of the IEEE/MTS OCEANS 2010*, Sept 2010, pp. 1–3.
- [12] N. Cruz, A. Matos, R. Almeida, B. Ferreira, and N. Abreu, "Trimares - a hybrid auv/rov for dam inspection," in *Proceedings of the IEEE/MTS OCEANS 2011*, Kona, Hawaii, USA, Sept 2011, pp. 1–7.
- [13] D. Ribas, N. Palomeras, P. Ridao, M. Carreras, and A. Mallios, "Girona 500 auv: From survey to intervention," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 1, pp. 46–53, Feb 2012.
- [14] J. Kinsey, D. Yoerger, M. Jakuba, R. Camilli, C. R. Fisher, and C. German, "Assessing the deepwater horizon oil spill with the sentry autonomous underwater vehicle," in *Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, San Francisco, USA, Sept 2011, pp. 261–267.
- [15] A. Bowen, D. Yoerger, C. Taylor, R. McCabe, J. Howland, D. Gomez-Ibanez, J. Kinsey, M. Heintz, G. McDonald, D. Peters, J. Bailey, E. Bors, T. Shank, L. Whitcomb, S. Martin, S. Webster, M. Jakuba, B. Fletcher, C. Young, J. Buescher, P. Fryer, and S. Hulme, "Field trials of the nereus hybrid underwater robotic vehicle in the challenger deep of the mariana trench," in *Proceedings of the IEEE/MTS OCEANS 2009*, Biloxi, USA, Oct 2009, pp. 1–10.
- [16] G. Meinecke, V. Ratmeyer, and J. Renken, "HYBRID-ROV Development of a new underwater vehicle for high-risk areas," in *Proceedings of the OCEANS MTS/IEEE Conference 2011*, Kona, Hawaii, May 2011, pp. 1–6.
- [17] M. Hildebrandt, C. Gaudig, L. Christensen, S. Natarajan, P. Paranhos, and J. Albiez, "Two years of experiments with the AUV DAGON - a versatile vehicle for high precision visual mapping and algorithm evaluation," in *IEEE/OES Workshop on Autonomous Underwater Vehicles (AUV) 2012*, Southampton, UK, Sept 2012, pp. 1–9.
- [18] M. Hildebrandt, J. Albiez, M. Fritsche, J. Hilljegerdes, P. Kloss, and F. Kirchner, "Design of an autonomous under-ice exploration system," in *Proceedings of the IEEE/MTS OCEANS 2013*, San Diego, USA, Sept 2013, pp. 1–7.
- [19] J. Albiez, S. Joyeux, and M. Hildebrandt, "Adaptive AUV mission management in under-informed situations," in *Proceedings of the OCEANS MTS/IEEE Conference 2010*, Seattle, Sep. 2010, pp. 1–6.
- [20] G. Meinecke, J. Albiez, S. Joyeux, V. Ratmeyer, and J. Renken, "OROCOS based control software of the new developed MARUM hybrid-rov for under-ice applications," in *Proceedings of the IEEE/MTS OCEANS 2013*, San Diego, USA, Sept 2013, pp. 1–7.
- [21] S. Joyeux, "Building complex systems with single-purpose components," in *Proceedings of the 2013 Workshop on Software Development in Robotics at ICRA*, 2013.
- [22] S. Joyeux and J. Albiez, "Robot development : from components to systems," in *Control Architecture of Robots*, 2011, pp. 1–15. [Online]. Available: <http://hal.inria.fr/inria-00599679>
- [23] T. Watanabe, G. Neves, R. Cerqueira, T. Trocoli, M. Reis, S. Joyeux, and J. Albiez, "The rock-gazebo integration and a real-time AUV simulation," in *Proceedings of the 12th Latin American Robotics Symposium*, Oct 2015, pp. 1–6.
- [24] A. Duda and J. Albiez, "Back projection algorithm for line structured light extraction," in *Proceedings of the IEEE/MTS OCEANS 2013*, San Diego, USA, Sept 2013, pp. 1–7.
- [25] J. Albiez, A. Duda, M. Fritsche, F. Rehrmann, and F. Kirchner, "CSurvey – an autonomous optical inspection head for AUVs," *Robotics and Autonomous Systems*, vol. 67, pp. 72 – 79, 2015, advances in Autonomous Underwater Robotics.
- [26] L. Christensen, C. Gaudig, and F. Kirchner, "Distortion-robust distributed mangetometer for underwater pose estimation in confined UUVs," in *Proceedings of the MTS/IEEE OCEANS 2015*, Washington DC, USA, Oct 2015, pp. 1–7.