Sabertooth a Seafloor Resident Hybrid AUV / ROV System for Long Term Deployment in Deep Water and Hostile Environments.

Jan Siesjö, Saab Underwater Systems AB - Chris Roper, Saab Seaeye Ltd.
Contributions from Marcus Furuholmen Aker Solutions AS

Abstract

Increasing use and complexity of subsea installations has put focus on the costs of maintaining these systems. In addition, access to these systems is sometimes limited by adverse weather and ice conditions. Conventional methods for intervention, maintenance and repair (IMR) using surface ships and ROV's are very expensive furthermore response and mobilization times can be fairly slow.

To address this Saab Underwater Systems has developed a hovering Hybrid AUV/ROV system to remotely perform IMR without or strongly reduced need for a supporting ship. This system is based on the Double Eagle SAROV, a hovering Hybrid AUV/ROV in production for the military market and proven components from Saab Seaeye ROV product range.

This paper will present the Seaeye Sabertooth subsea resident AUV/ROV system, its concept of operation, design and the cooperation project between Saab and Aker Solution. It will also present the ongoing Sabertooth tests and trials conducted together with Tecnomare and Chevron.

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1 Background

The Double Eagle Family utilizes the Saab modular approach to provide a flexible system for Mine Counter Measures (MCM) operations. Over the last 15 years more then 70 of these systems have been sold worldwide. 30 of these systems are used in a Propelled Variable Depth Sonar (PVDS) configuration including functions such as autopilot (waypoint, station keeping), automatic tether management, and auto altitude, using a tether. They are operated under complete automatic control by following a track of waypoints or put in a station keeping mode, receiving coordinates from an operator console. The tether in this application is used for power and to provide real time sonar data.

The Double Eagle SAROV (Saab Autonomous ROV) is an upgrade of the existing Double Eagles enabling tether-less operation. This system has been through testing and trials and has performed a large number of missions. These include traditional sonar surveys, video recording of targets and tether docking trials. The first system of this type has been sold to the Danish Navy.

The Double Eagle SAROV is the military version and the commercial version has been named the Seaeye Sabertooth.

The Seaeye Sabertooth is a merge of the Double Eagle SAROV and the Saab Seaeye technology resulting in a hovering AUV with rugged design and deeper depth capacity. The Seaeye Sabertooth is based on the same thrusters as the popular Seaeye Cougar ROV and the full 6DOF manoeuvrability of the Saab Double Eagle and Sea Owl ROV's. This makes it a very powerful but lightweight platform for both inspection and light IMR tasks. Its small size, tether less operation and manoeuvrability gives easy and safe access inside complex structures.

Saab is working closely with subsea equipment manufacturer Aker Solutions on the concept development and on ways to practically develop the Seaeye Sabertooth technology. A full-scale integration on selected subsea production systems is expected to contribute to Aker Solutions life cycle service philosophy.

Two single hull versions have been built. One of the versions (denominated SUBROV) includes a submerged fibre optic winch, see Figure 1 and Figure 2. This system has been thru several tests and trials and integration trials are now underway to operate it from a submarine torpedo tube.

The other single hull configuration has been delivered and is configured for tunnel inspections, Figure 3 Seaeye Sabertooth Single Hull

One Sabertooth Double Hull (DH) has been designed and built. Tests and trials with electromagnetic communication and inductive power transfere are ongoing.

Figure 1 SUBROV being loaded in submarine.

Figure 2 SUBROV on torpedo tube docking skid with winch.

Figure 3 Seaeye Sabertooth Single Hull

Figure 4 Seaeye Sabertooth Double Hull

2 Concept of Operation

The system has three operational phases:
In the transit phase, a combination of IMU/Doppler and terrain navigation allows the vehicle to transit 10+ nautical miles (20 km) with meter accuracy.

In the approach phase, optical or long wave radio communication (50 m range) between the Seaeye Sabertooth and the DS allows an onshore operator to monitor the operation.

The docking is done in either operator-assisted or in manual mode. When docked, the Seaeye Sabertooth is recharged and data may be up- or downloaded.

The Seaeye Sabertooth can be operated in three different modes - autonomous, operator-assisted and manually.

In autonomous mode, the vehicle is instructed to perform a specific task such as to transit to a specific location or to perform a pre-programmed inspection/survey. The autonomous system uses behaviour based control architecture.

In operator-assisted mode, the vehicle is given step by step instructions from an on-shore operator, such as move forward 3 meters, turn right etc. Operations are subjected to behavioural constraints such as minimum distance to surroundings, minimum altitude, speed etc. Each step is then verified by video or sonar data and sent back through low bandwidth communication.

In manual operation, the vehicle is operated manually through a tether, using optical communication or a radio link, but with assistance from local Inertial Measurement Unit (IMU) and/or Doppler. This will allow for slow (limited by bandwidth) operation. This mode can be typically used during the final approach to the docking nodes as well as during e.g. operations of valves.

3 Design

3.1 General

The system design is based on the following requirements and assumptions:

- The system shall be able to do visual inspection of an entire Subsea Production System (SPS).
- The system shall be able to do operation of manually operated valves in auxiliary piping.
- The system shall be able to operate valves inside the SPS.
- The AUV shall remain on the bottom for at least 12 months without requiring service.
- The docking station shall remain on the bottom for at least 5 years.
- The system shall allow future addition of new functionality.

This leads to the following conclusions:

- The bottom time requirements (reliability), means that the system, as much as possible, is based on existing proven technology with low technical risk. The system is built using similar methotds to those used in the aircraft related production of Saab.
- To be able to add more future functionality, the AUV has spare capacity in the same way as a conventional ROV (performance and interface), to be able to carry new tool and sensor packs. The docking station is built in such a way that it allows new payloads both on top and below the AUV body.
- Some inspection tasks, and even some valve operations, could possibly be performed autonomously. However, to maximize the number of tasks possible, minimize technical risk and generally speed up operations, the system uses a communications network. This allows operation with low bandwidth wireless communication and higher bandwidth communication using optical systems.

The system design has the following main elements:

- Seaeye Sabertooth AUV
- Operator station see Figure 6 Typical Operator Station.
- Docking station see Figure 5 Docking Station
- Communications network

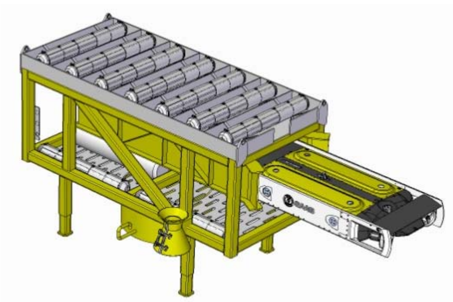

Figure 5 Docking Station

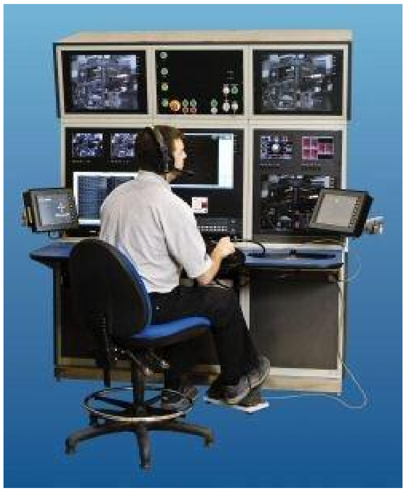

Figure 6 Typical Operator Station.

3.2 Vehicle

3.2.1 General

The Sabertooth is a combination of parts from the Saab Seaeye Cougar XTi ROV, the single hull SUBROV and the Double Eagle SAROV hybrid AUV.

The following components come from the Double Eagle SAROV:

- Battery
- Onboard battery charger
- Control system with dynamic positioning
- Doppler/IMU navigation system
- Obstacle avoidance system
- Onboard video/sonar recording system

The following components come from the Cougar XTi:

- SM9 Thrusters
- Cameras
- LED Lights
- Tool and payload interfaces

The following components come from the SUBROV:

- Pressure hulls
- Framework design

In addition to this there are some parts that are specific for the Seaeye Sabertooth. These are:

- Non galvanic docking device
- Electromagnetic communication antenna, see 3.5
- Short communication tether, see 3.5
- Optical communication

The non galvanic docking device is an inductive coupling to transfer power to the AUV from the docking station. This is a disk/cylindrical device with no exposed metal, covered in polymer coating. The disk is brought into close proximity of a similar device on the docking station. This then allows power of up to 5 kW to be transferred to the AUV.

The software and control system comes from the Double Eagle SAROV. This software allows the AUV to be operated both with manual control and using behaviour based autonomous functionality based on the following capabilities:

- Waypoint following
- Station keeping
- Obstacle avoidance
- Sonar homing
- Sensor interaction
- Tunnel or object following
- 6 DOF manoeuvrability
- Auto heading, attitude, altitude, depth

In addition to this functionality some additional behaviour will be added. These may include navigation with respect to communication nodes, enhanced sonar feature navigation and emergency procedures. The details of these need to be worked out in a test, simulation and trials phase based on actual tasks and a defined structure.

3.2.2 Sensors

The Seaeye Sabertooth is equipped with the following main sensors:

- 4-6 fixed cameras. Use of multiple fixed cameras is preferred to keep the design robust and add redundancy.
- Electronically scanning imaging and obstacle avoidance sonar. Electronically scanning sonar is preferred to avoid moving parts. Separate imaging and obstacle avoidance sonars give redundancy.
- DVL/IMU, Doppler Velocity Log)/Inertial Measurement Unit. Primary navigation sensor. The DVL may also be used to measure water

flow and temperature. The IMU may also be used to measure low frequency vibrations.

- Pressure sensor. Primary sensor for determining depth.
- Hydrophone. Valuable self monitoring tool. Could also be used to record sound during inspection runs.

3.2.3 Navigation

In autonomous mode, the Seaeye Sabertooth will rely on passive communication nodes/landmarks for local navigation on the SPS. Such passive communication nodes may be Sonar reflectorts (Sonar bells) or Radio Frequency Identification (RFID) tags which may be implemented on subsea equipment. Sonar reflectors are distinct geometric shapes (polyhedrons or resonance spheres i.e Sonar Bells) that may be allocated on different parts of the structure. The reflectors provide the Seaeye Sabertooth with a recognizable signature for navigation. The use and implementation of passive navigation provides an inexpensive and robust navigation system.

3.3 Operator Console

A typical operator console is shown in Figure 6. This is very similar to a conventional ROV console. The difference is that a conventional ROV console normally has multiple video screens while the Seaeye Sabertooth console has multiple computer screens to display mission planning data, 3D visualization, sonar and video data.

Figure 7 Photo of Seaeye Sabertooth status screen.

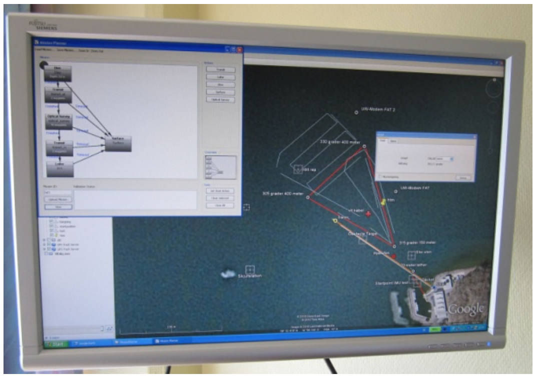

Figure 8 Photo of Seaeye Sabertooth mission planning client with Google Earth as display tool.

Figure 9 Joysticks for manual control.

3.4 Docking Station

The AUV Docking Station (AUVDS) is where the Seaeye Sabertooth resides in between missions. While in the AUVDS the Seaeye Sabertooth is recharged and data can be up and downloaded.

The docking station is designed in such a way that it both provides a secure stowing place and at the same time is as open as possible for existing and future tools and payloads. The docking station allows new tools and payloads to be mounted on top, on the bottom and on the front and back of the Seaeye Sabertooth, see Figure 11.

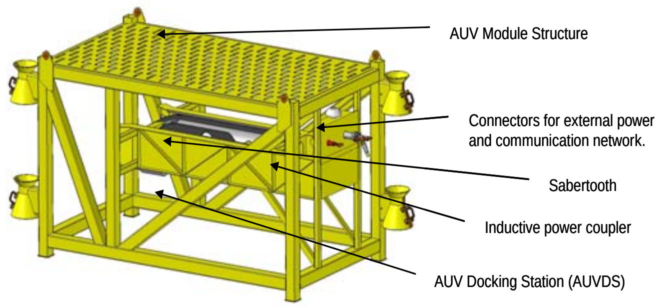

Figure 10 Rear /Side view of the AUV Module.

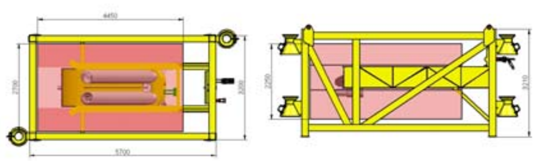

Figure 11 View of docking station showing reserved payload space.

The size of the Seaeye Sabertooth and the required tools packs are decisive for the dimensioning of the AUV Module Structure, which will cover the AUV Docking Station. The AUVDS needs a protective structure which is in accordance with subsea protection philosophy.

The AUVDS will have two sets of connectors for redundancy. The connectors will be wet mate connector such as e.g. the Rolling Seal connectors from ODI which contains both power and optic communication. In addition, there will be a set of connectors to interface to the communications network.

The functions in the electronics module on the AUVDS will be kept as simple as possible. A subsea control module already developed by Aker Solutions may be used for this. It should have the following parts/functions:

- Power transformer/switching
- Ethernet switch
- Interface to electromagnetic communication antennas and network

3.5 Communication

The communication system is based on using a combination of several communication systems. These are optical communicaton based on blue green LED or laser transmitters. These will give relatively high bandwith at medium to short distances. Electromagnetic transmitters and receivers give shorter range but are not sensitive to water conditions, silt and marine growth. Acousic communications is used as a complement at longer range for simple commands and status updates. For transit to and from the structure no additional communication needs are foreseen since this transit is done autonomously.

Electromagnetic communication has successfully been used in military applications underwater and underground in the past. The placement and number of nodes need to be tested and analysed in relation to the specific conditions on the SPS before a final configuration can be set.

Figure 12 Example of communication antenna from WFS.

The electromagnetic communication antenna is a cable loop with electronics that is built into the framework of the AUV. This allows data to be transmitted and received from the docking station and the communication nodes on the structure. When in close proximity to the docking station, high bandwidth communication is possible, allowing data to be downloaded from the AUV. Data rates will be in the 10 Mb range.

Testing of electromagnetic communication and power transfer is currently in progress

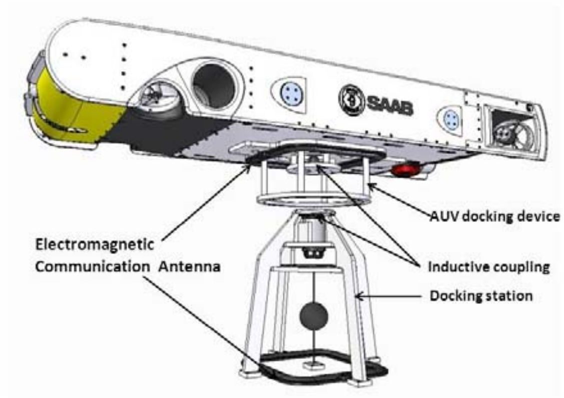

Figure 13 Saabertooth with docking device for data harvesting currently under test

Even though improvements can be expected in the autonomy of future AUV systems they will nonetheless benefit from a robust communication system. Investing in a communication network will speed up operations and make them safer since feedback can be sent back.

Redundancy in the communications system is provided by overlapping node spacing of optical or electromagnetic antennas or the use of a short communication tether as described below.

In Figure 14 below the short communication tether function is illustrated. The data rate that is achievable with an electromagnetic communication system is highly dependent on range. Therefore, to be able to guarantee high bandwidth communications for certain operations the AUV has a short communication tether installed. This tether is deployed by a small TMS built into the Seaeye Sabertooth, much in the same way as the power chord of a vacuum cleaner. At the end of this tether there is an antenna that will provide high bandwidth communication provided that it is within a close proximity of a communications node. The AUV can thus attach its antenna in a hook located near the communications node. Then it can swim off to a work location nearby maintaining communication. In order to keep the system as simple and reliable as possible the length of this tether will be kept to 10-15 m (longer lengths could be possible but this would be tried out and studied when more is known about required tasks).

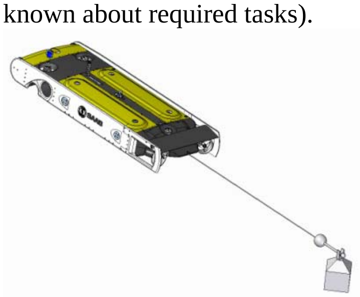

Figure 14 Illustration of short communication tether principle.

The expected bandwidth of the communications network is around 100 kb. This is enough for manual control and compressed low resolution video and sonar images. Higher resolution images can be transmitted as well but with a delay.

Figure 15 Sample of a JPEG compressed 10 kB image that takes 1 second to upload on a 100 kb link.

3.6 Tools

3.6.1 Torque tool

Electric class 4 torque tools have been operated from the Saab Sea Owl Mk IV for over 10 years.

Figure 16 Saab Sea Owl with torque tool.

The Sea Owl is a small ROV 120 kg and 1.3 m long. On the Sea Owl the torque tool is mounted under the ROV with only a telescopic extension possible. Orientation of the tool is handled by the 6 DOF onboard control system.

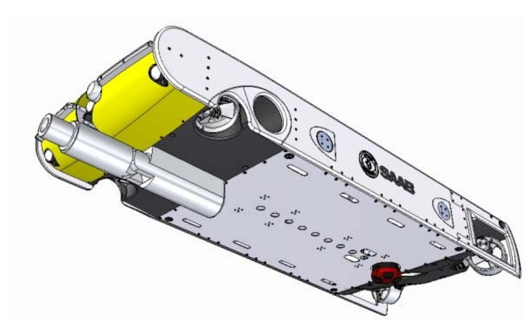

Figure 17 Seaeye Sabertooth with torque tool

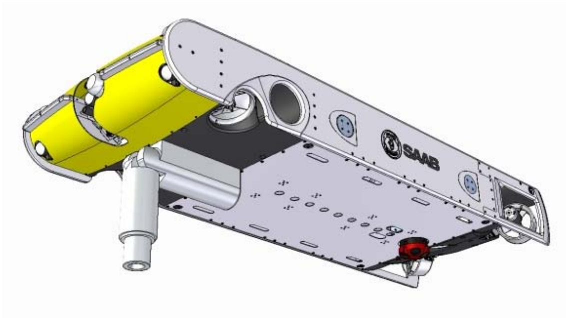

Figure 18 Seaeye Sabertooth with torque tool at 90 degrees.

The same principle is used on the Seaeye Sabertooth. Depending on access requirements the torque tool may also be provided with a rotating function allowing it to direct the tool up to 90 degrees from the AUV body.

Bending loads on the valve is limited by a number of design features:

- The weight and size of the Seaeye Sabertooth is relatively small compared to a WROV.
- It is neutrally buoyant, therefore the only outside forces that can cause bending torque is hydrodynamic drag due to sea currents and thruster action.
- The drag forces expected from a 1 knot current is less than 300N. This is far less than the forces that could be induced by a WROV hydraulic manipulator and it can be easily offset by a small balancing thrust from the AUV.
- The torque tool has a flexible joint allowing angular movement of the AUV without inducing high bending load.

Electric torque tools are available today from iFocus/Oceaneering AS and under development at Saab Seaeye. The torque tool is for CL 4 valve interfaces, but the toque tool can be used as an interface for connection to other tools as well, such as tool for operating CL 7 valves. Alternatively, a CL 7 torque tool may be attached as a tooling skid.

Figure 19 Electric torque tool from iFocus/Oceaneering AS.

3.6.2 Future tool and sensor potential

Depending on size and other requirements, other tools and sensors could be added as fixed tools or as dockable tools. This includes e.g. CL 7 torque tool, tools for non Destructive Testing (NDT) and Hydrocarbon leak detectors.

3.6.2.1 Tool skid docking

The same principles that are used for communication and power transfer on the AUV itself can be used for dockable AUV tool skids. Communication can use the same antennas already installed for the communication network. In addition, the tool skids could have built in batteries. Using built-in batteries enables tools with high intermittent power to be used. In addition, using built in batteries and communication compatible with the communications network, allows tools and sensors to work independent of the AUV. This opens up the possibility to deploy multiple mobile tools and sensor platforms, using the AUV to move them around and recharge.

Tool skids would only require a simple protective structure for storage.

3.6.2.2 AUV retrieval

Since the Seaeye Sabertooth is an AUV capable of longer excursions, new tools could be mounted by ordering the Seaeye Sabertooth to an adjacent platform or ship. The Seaeye Sabertooth would then be retrieved in the same manner as an ROV. Onboard the ship a new set of tools or sensors could be fitted. The Seaeye Sabertooth would then be launched and programmed to return to the SPS. If recharged on the ship or platform the range possible for such an operation is approximately 50 km.

4 Technical data

Specifications	Seaeye Sabertooth
Depth rating	500 msw (3 000 msw optional)
Length	3 400 mm
Height	650 mm
Width	1 200 mm
Launch weight	650 kg
Forward speed	5 knots
Thrust forward	100 kgf
Thrust lateral	90 kgf
Thrust vertical	160 kgf
Battery capacity	20 kWh (3-10 hours)
Range	20-50 km
Payload	80 kg (nominal excess buoyancy offset by lead weights)

Table 1. Technical Data Seaeye Sabertooth.

Specifications	Operators Console
Power	2kW 240VAC (preliminary)
Network to Docking Station	100MB Ethernet

Table 2. Technical Data Operators Console.

Specifications	Docking Station
Power	2-10kW 3phase 400VAC (preliminary)
Network to Docking Station	100MB Ethernet
Depth rating	1 500 msw (3 000 msw optional)
Height	3 200 mm (preliminary)
Width	3 200 mm (preliminary)
Length	5 700 mm (preliminary)

Table 3. Technical Data Docking station.

5 Sample scenarios

5.1 Launch and recovery

Launch and recovery from a surface ship or platform is done in the same manner as a normal ROV. A standard ROV garage type TMS fitted with the same inductive communications devices as the docking station is used for both launch and recovery. The garage would be tracked from the ship using an acoustic tracking system. The Seaeye Sabertooth would then be programmed to intercept at the garage coordinates. The final approach is then done using the optical communications system assisted by the onboard obstacle avoidance/navigation sonar.

Figure 20 A-frame with ROV TMS garage.

Inspection runs can be done in autonomous, semi autonomous, manual or in a combination mode. A typical inspection run would contain the following operations:

- Programming: A pretested and simulated mission description would be downloaded to the Seaeye Sabertooth while it is still in the docking station. The use of pretested and simulated mission descriptions reduces the risk for operator errors and increases efficiency. Repeatability, and the possibility of comparing new and previous inspection results increases.
- Transit: The Seaeye Sabertooth does an autonomous transit to the inspection site. In this phase the Seaeye Sabertooth is guided by the DVL/IMU together with the obstacle avoidance/navigation sonar. Progress can be followed by the operator thru the use of the acoustic communications system. For long transits the Seaeye Sabertooth will be out of range of the communications system. The DVL/IMU navigation system will allow this transit to be done with a precision of < 2 m.
- Inspection: If close up or other specific tasks are to be done then the Seaeye Sabertooth stops 2 m from the object to be inspected and waits for the operator to take control. Otherwise, the Seaeye Sabertooth will simply stop, record video, picture and sensor data for a predetermined time at the object. Low resolution data is continuously sent back to the operator while high resolution data is stored onboard for later upload in the docking station. In manual or semi autonomous mode video and sonar data are transmitted back to the operator by the optical or inductive communication system. This means that there may be a small delay (1-2 seconds depending on resolution) on the feedback. The onboard control system, however always keeps the Seaeye Sabertooth stable and in position. This allows the Seaeye Sabertooth to be commanded slowly, and a step at the time, towards and around an object. As long as no new input is received from the operator the Seaeye Sabertooth remains in the same position.
- Return and docking: When the operation is completed the Seaeye Sabertooth is commanded to return to the docking station. This is done in the same way as the transit. The Seaeye Sabertooth will autonomously and safely go back to the docking station following a pre-programmed and pretested path. The Seaeye Sabertooth will stop 2 m in front of the docking station and await the operator to take control. Here it is near the communication antenna in the docking station, and the operator can fly the Seaeye Sabertooth into the dock in manual mode. Docking can, if desired, also be done autonomously.

5.2 Valve operation

Valve operation is done in a similar manner as inspection. The difference is that for valve operation the Seaeye Sabertooth is brought into physical contact with the structure. A typical valve operation is described below:

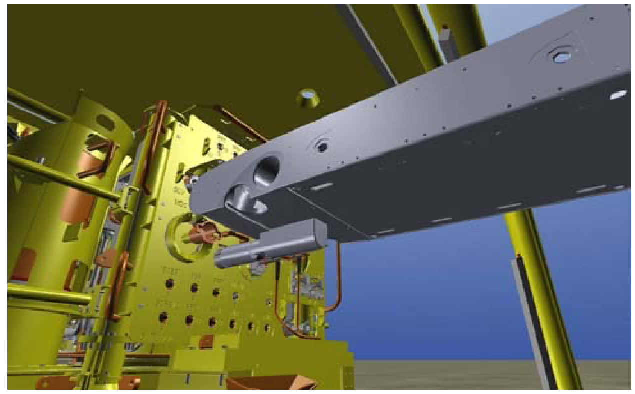

Figure 21 Sabertooth close to a valve panel. Picture Courtesy from Aker Solutions

- The Seaeye Sabertooth transits to the inlet isolation valve in autonomous mode. Transit is monitored by the operator.
- The Seaeye Sabertooth stops 2 m from the valve and awaits operator to take control.
- The Seaeye Sabertooth is then instructed to move forward 1.5 m. Position and video is checked.
- The Seaeye Sabertooth is instructed orient the torque tool downwards. Because of the low metacentre height of the Seaeye Sabertooth and the active 6 DOF control system the vehicle operates just as well in any orientation. The control system translates commands from the operator, allowing easy operation. Since the torque tool can be rotated it allows access to valves in a very flexible manner.

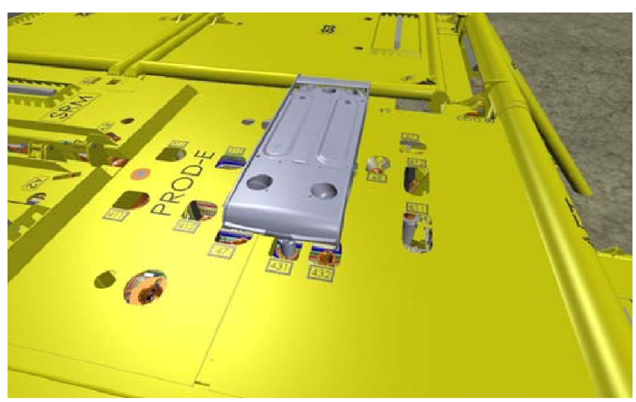

Figure 22 Sabertooth above SPS. Picture Courtesy from Aker Solutions

- Fine adjustment of the position is preformed to line up the torque tool with the valve. The onboard control system keeps the Seaeye Sabertooth stable and at a set position.
- The Seaeye Sabertooth is slowly lowered mating the torque tool into the valve.
- The small size and weight of the Seaeye Sabertooth allows it to be docked to the valve. A small thrust may be used to offset forces due to water currents.
- The valve is operated with real time feedback being sent back to the operator thru the optical or inductive communication system.
- After a completed operation the Seaeye Sabertooth is instructed to return to the docking station or to another valve or inspection point.

6 Ongoing tests and trials with Sabertooth DH

6.1 Data harvesting

In a Chevron sponsored project Saab and WFS are performing trials to test the essential operations needed to do a successful dataharvesting operation.

These tests consist of the following:

- **Navigation, homing and docking:** The Sabertooth will autonomously navigate to a known sensor location. At this point it will search and relocate the sensor (marked by a Sonarbell). It will then home in and either do a flyby and retrieve data wirelessly or physically dock to the sensor platform and initiate data transfer as well as do a power transfer (recharge of the sensor).
- **Power transfer:** A couple of different alternatives to inductive power transfer will be evaluated.
- **Inductive communication:** Useful range and behavior of a WFS inductive communication system will be tested and evaluated on the Sabertooth. This will be done in both lake and real sea conditions.

A WFS communication device has been integrated on Saabertooh for tank, lake and sea trials. The tests shall show that an acceptable data rate and range is achievable when the device is integrated on the Sabertooth.

Figure 23 Sabertooth docked to sensor test platform

A sensor dummy interface structure has been designed and built. The structure contains a “pancake” shaped coil and a container with the necessary electronics inside. The structure is also equipped with a sonar bell to facilitate for the vehicle to find the docking structure.

The software in Sabertooth has been upgraded to make it possible for autonomous homing and docking tests.

6.2 CLEAN-SEA

Clean-sea is a EniNorge sponsored project carried out by Tecnomare involving the concept of an innovative robotic system making possible the execution of environmental monitoring tasks around oil&gas installations by means of an AUV.

Saab and Tecnomare are currently in the process of completing phase 1 of these trials.

The concept is based on commercial AUV upgrade with key enabling technologies such as:

- Environmental sensors
- Inspection sensors
- Communication (inductive, acoustic)
- Reactive control
- Homing and navigation

Reference missions addressed by the project include:

• Environmental monitoring tasks, during all phases of the field development: prior to any activity taking place (environmental baseline monitoring); during exploration and production activities, in proximity of offshore infrastructures (platforms, FPSO, SPS, pipelines etc.) (environmental impact monitoring); in the event of significant incidents, to record the immediate effects of the incident and environmental recovery (post-incident monitoring).

• General oil spill detection tasks, pre-planned paths, along flowlines, around SPS templates and manifolds.

• Detection and localization of hydrocarbon leakages from flowlines
• Visual inspection tasks of SPS structures such as ROV panels on manifolds or similar.

To solve this task Sabertooth wil be equipped with a number of different sensors:

- CTD, Conductivity, Temperature and Depth
- Turbidity and florescene (Chlorophyll, CDOM), cloudiness (water quality) pH/O.R.P
- Dissolved Oxygen
- Fluorescence (oil in water), detection of hydrocarbons and carbon dioxide
- Methane sensor
- Mission Control Unit

Besides the sensors mounted directly on the vehicle the system consist of an interchangeable instrumented module (E-pod) and the Payload Control Unit. Each E-pod contains a set of sensors and analyzers mounted beneath the vehicle.

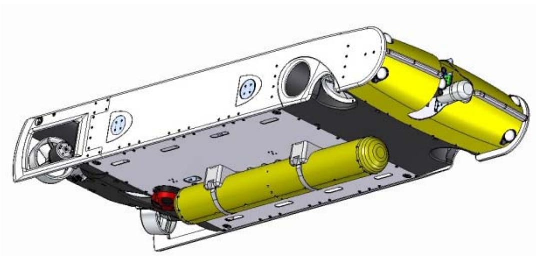

Figure 24 Sabertooth with E-pod for Clean-sea missions.

Tests and trials are ongoing with the Cleans-Sea equipment in the lake Vettern in south of Sweden.

Figure 25 Sabertooth with sensor pod being launched from quay.

Figure 26Sabertooth returning from mission

Figure 27 Sabertooth mobile test site consists of a small control van and a lorry with crane

Figure 28 Sabertooth controls set up in van