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Multi-Sonar Integration and the Advent of Sensor Intelligence

Edward Thurman, James Riordan and Daniel Toal
*Mobile & Marine Robotics Research Centre
 University of Limerick,
 Ireland*

1. Introduction

The subsea environment represents the last major frontier of discovery on Earth. It is envisioned that exploration of the seabed, in both our deep-ocean and inshore waters, will present a multitude of potential economic opportunities. Recent interest in the ever-expanding exploration for valuable economic resources, the growing importance of environmental strategies and the mounting pressure to stake territorial claims, has been the main motivation behind the increasing importance of detailed seabed mapping, and rapid advancements in sensor technology and marine survey techniques (McPhail, 2002; Nitsche et al., 2004; Desa et al., 2006; Niu et al., 2007).

Over the past decade, there has been an increasing emphasis on the integration of multiple sonar sensors during marine survey operations (Wright et al., 1996; Laban, 1998; Pouliquen et al., 1999; Yoerger et al., 2000; Duxfield et al., 2004; Kirkwood et al., 2004). The synergies offered by fusing and concurrently operating multiple acoustic mapping devices in a single survey suite underpin the desire for such an operational configuration; facilitating detailed surveying of the ocean environment, while enabling the information encoded in one instrument's dataset to be used to correct artefacts in the other.

Innovative advancements in the intelligence of sensors have permitted time-critical decisions to be made based on the assessment of real-time environmental information. In-mission data evaluation and decision making allows for the optimisation of surveys, improving mission efficiency and productivity.

While low-frequency (<200kHz) sonar has a long range imaging capability, the generated datasets are inherently of low resolution, reducing the ability to discriminate between small-scale features. Conversely, high-frequency (>200kHz) imaging sonar generates high-resolution datasets, providing greater detail and improving data analysis. High-frequency sonar systems are therefore the desired sensor systems used during seabed survey missions. However, seawater severely restricts acoustic wave propagation, reducing the range (field of view) of high-resolution sonar in particular. Consequently, high-resolution survey sensors must be deployed in close-proximity to the seabed. UUVs are ideal platforms for providing the near-seabed capability required, and often demanded, by marine survey operations (McPhail, 2002). Furthermore, recent technological advancements have allowed UUVs to provide high-resolution survey capabilities for the largely unexplored deep-water environments, previously considered uneconomical or technically infeasible (Whitcomb, 2000).

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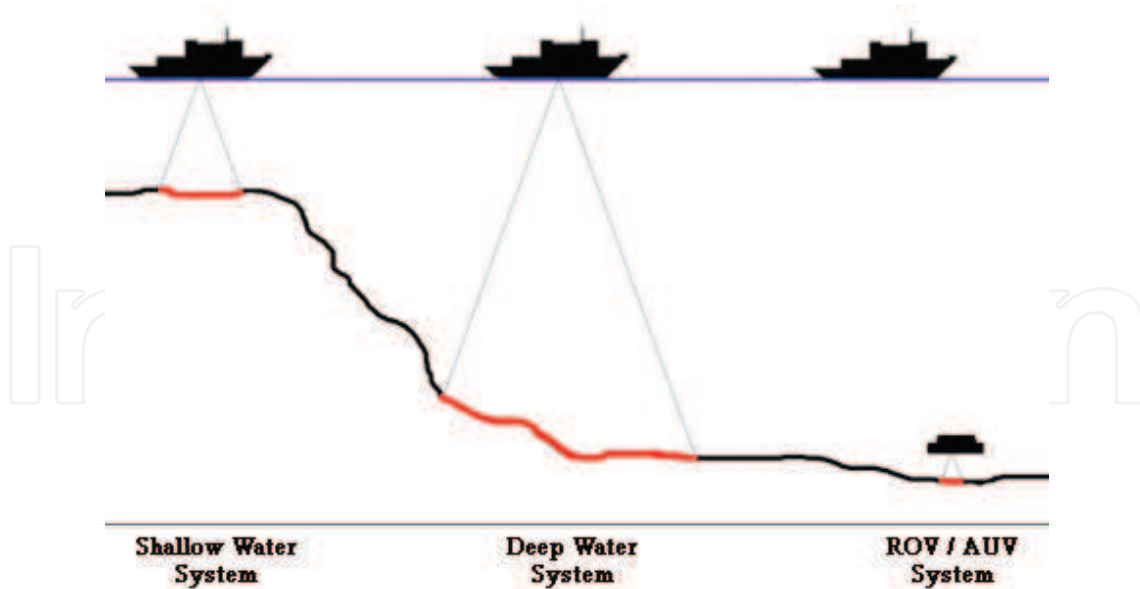


Fig. 1. Comparison of sonar systems operating at different depths. Notice the increasing footprint as the distance increases. However, as the distance increases, the operating frequency of the sonar must decrease, as seawater severely restricts acoustic wave propagation, resulting in lower resolution datasets.

	Water Depth	Operating Frequencies	Resolution	Swath Coverage	Remarks
Shallow Water Systems	< 100m	> 200kHz	Medium - High	Low - Medium	Continental shelf, inshore-water seabed surveying
Deep Water Systems	> 200m	< 200kHz	Low	High	Wide-area, deep-ocean seabed surveying
ROV/AUV Systems	5m - 4000m	200kHz - 500kHz	High	Low	Detailed, high-resolution seabed surveying

Table 1. Comparison of typical operating specifications for sonar systems operating at different depths.

However, the operation of multiple co-located, high-frequency acoustic sensors results in the contamination of the individual datasets by cross-sensor acoustic interference. The development of sensor control routines and 'intelligent' sensors helps to avoid this sensor crosstalk.

This chapter details the modern sonar technologies used during survey operations of today and the integration of these sensors in modern marine survey suites. The problems associated with integration of multiple sonar sensors are explained, and the sensor control routines employed to avoid such problems are discussed. Finally, the future direction of payload sensor control and the development of intelligent sensor routines are presented.

2. Sonar technologies

Due to the high attenuation of electromagnetic waves underwater, video and radar are unsuitable for wide-area mapping of the subsea environment. Instead, acoustic waves are the only practical way to chart wide areas of the seafloor. Sonar technology is an essential part of a modern marine survey system and has been successfully employed to record the composition, physical attributes, and habitat and community patterns of our ocean seabeds. Today, there are numerous acoustic devices available for charting the seafloor including multibeam echosounders, sidescan sonar, interferometric sonar and synthetic aperture sonar. These systems differ in their acoustic mapping techniques and capabilities, and provide diverse interpretations of the seabed. The different acoustic techniques, applications and survey capabilities of modern sonar technologies are briefly detailed below:

2.1 Multibeam echosounders

Multibeam echosounders are capable of collecting highly accurate seafloor depth information. Over the last number of decades these systems have been successfully used for gathering high-resolution seafloor bathymetric data in shallow- and deep-water regions (Hammerstad et al., 1991; Laban, 1998; Kloser, 2000; Parnum et al., 2004). The multibeam sonar system emits an acoustic pulse wide in the across-track field and narrow in the along-track field, producing a “cross fan” beam pattern to obtain detailed coverage of the bottom. The receive beam pattern is wide in the along-track field and narrow in the across-track field. The resulting product of the transmit and receive beams is a narrow beam that ensonifies an area of the seafloor, providing range-angle couplets of sample points (over 500 individual points in some systems) along the swath. Multibeam sonar systems are also capable of supplying acoustic backscatter imagery, by recording the intensity of the backscattered signal as it is swept along the seabed. However, the image is of lower resolution and poorer quality than the sidescan sonar backscatter image (Smith & Rumohr, 2005). Multibeam systems are also expensive and require high processing power.

2.2 Sidescan sonar

Sidescan sonar is an acoustic imaging device used to produce wide-area, high-resolution backscatter images of the seabed, under optimal conditions it can generate an almost photo-realistic, two-dimensional picture of the seabed. This acoustic instrument is used for charting seabed features and revealing special sediment structures of both biogenic and anthropogenic origin (McRea, 1999; Brown et al., 2004; Smith & Rumohr, 2005). Sidescan does not usually produce bathymetric data. However, it does provide information on sediment texture, topology, bedforms and the low grazing angle of the sidescan sonar beam over the seabed makes it ideal for object detection (Kenny, Cato et al. 2003). One disadvantage of sidescan sonar is that it does not provide reliable information on the position of seabed features.

2.3 Interferometric sonar

Interferometric systems are capable of providing high-resolution, wide-swath bathymetry in shallow water with swaths of 10 - 15 times the instrument altitude (Gostnell et al., 2006). Interferometry is the technique of superimposing (interfering) two or more waves, to detect differences between them. Measurement of the difference in acoustic path allows the

accurate assessment of the angular direction. Interferometric technology could prove highly beneficial to seabed mapping programmes. However, it is still considered a developing technology within the marine industry. While there have been numerous papers written on the theoretical functionality of these systems and a variety of manufacturer studies conducted, there have been few independent analyses of their in situ performance (Gostnell, 2005).

2.4 Synthetic aperture sonar

The Synthetic Aperture Sonar (SAS) is a high-resolution acoustic imaging technique that combines the returns from several consecutive pings to artificially produce a longer sonar array. With the use of sophisticated processing, the data is used to produce a very narrow effective beam. The most important attribute of an SAS system is its along-track resolution being independent of both range and frequency. SAS is a direct analogue of synthetic aperture radar (SAR) processing, which is well established in both airborne and spaceborne applications (Curlander & McDonough, 1992) providing vast area coverage, imagery and bathymetry at high spatial resolution. For a generation, engineers have attempted to replicate SAR concepts with sidescan seafloor imaging sonars. However, SAS has long been considered a purely theoretical concept (Lurton, 2002) and its implementation was thought to be untenable due to lack of coherence in the ocean medium, precise platform navigation requirements and high computation rates. With advances in innovative motion compensation and autofocusing techniques, signal processing hardware, precise navigation sensors, and stable submerged autonomous platforms, SAS is now beginning to be used in commercial survey and military surveillance systems (Sternlicht & Pesaturo, 2004).

3. Sensor integration

The integration of multiple sonar sensors into a marine survey suite allows for the simultaneous collection, and fusing, of individual datasets of the same seafloor region. Accordingly, the provision, and combined analysis, of complementary and comparative datasets affords a more accurate representation of the seafloor, the removal of possible dataset ambiguities and improved data analysis and interpretation (Wright et al., 1996; Evans et al., 1999; Hughes Clarke et al., 1999; Dasarathy, 2000; Fanlin et al., 2003; Duxfield et al., 2004; Nitsche et al., 2004; Shono et al., 2004).

Data fusion is the process of taking information from multiple, independent datasets and combining it to extract information not available in single datasets; the combined analysis of contoured bathymetry maps, generated from multibeam echosounders, and the sidescan sonar acoustic reflectivity images permit the geologic interpretation of multibeam bathymetry data to be enhanced by providing an acoustic characterisation of the seafloor from which geologic composition can be inferred, while the bathymetric information improves the representation of the seafloor relief in sidescan imagery by providing the geometric configuration of the seabed (de Moustier et al., 1990; Pouliquen et al., 1999).

An integrated interpretation of acoustic datasets is presented by Nitsche et al. (Nitsche et al., 2004). According to the authors, the integrated examination of sidescan, sub-bottom and high-resolution bathymetry data enable the clear distinction of different seabed facies, and hence, an understanding of the related processes, vastly improving data interpretation and classification. Shono et al. (Shono et al., 2004) explore the synergies offered by an integrated hydro acoustic survey scheme, in which the survey region is mapped using a multibeam

echosounder and a sidescan sonar. The bathymetry data and sidescan imagery present complementary datasets of the seabed region, enhancing the individual, and combined, dataset analysis; affording a greater understanding of the seafloor region. The author also concludes that the integrated approach provides for a more economical and efficient survey. Wright et al, (Wright et al., 1996) present methods for performing multi-sensor data fusion. Through their investigations, the authors demonstrate that data fusion aids the classification and identification of seabed features, minimises dataset ambiguities and improves upon positional accuracy of the features present.

The integration of multiple sensors onto a single platform, such as a UUV, also minimises the relative positional error between features evident in the various datasets, as the target region is ensonified by the sensors under the same environmental conditions and georeferenced by the same navigational data. Simultaneous multi-sonar operation also eliminates the need to conduct separate surveys for each instrument, as well as the collection of supporting data required to fully understand the operating environment during each individual survey, thereby significantly reducing the survey duration and consequently the survey costs (Thurman et al., 2007).

Reports of successful AUV survey missions suggest that bathymetric mapping, sidescan imaging, magnetometer survey and sub-bottom profiling are the principle mission of the new survey-class AUVs (Whitcomb, 2000). To execute these missions, modern AUVs are typically equipped with a range of survey sensors, integrated into the single marine survey suite. The synergies offered by integrating and concurrently operating multiple acoustic mapping devices on a UUV underpin the desire for such an operational configuration, facilitating high-resolution surveys of the deep-ocean environment, while enabling the information encoded in one instrument's dataset to be used to correct artefacts in the other.

4. Acoustic interference avoidance

The reception circuitries of sonar transducers are typically frequency band-limited to prevent acoustic interference from parallel operating instruments of different frequencies. However, the high-resolution versions of most imaging sonar operate within the same frequency band, with typical working frequencies for high-frequency multibeam echosounders being 200kHz-400kHz, and high-frequency sidescan sonar ranging from 200kHz to 500kHz. While some instruments, such as multibeam echosounders, can be depth gated to filter spurious returns, sidescan sonar records can be severely distorted by sensor crosstalk, as they rely on the full temporal trace of the returned backscatter to construct an intensity image. Consequently, the simultaneous operation of multiple high-frequency sonar is prohibited by the inherent complication of cross-sensor acoustic interference (de Moustier et al., 1990; Ishoy, 2000; Kirkwood, 2007).

The integration and concurrent operation of multiple sonar sensors in a marine survey suite creates issues of cross-sensor acoustic interference. The contamination caused by sensor crosstalk severely degrades the resulting datasets of the parallel operating sensors. Traditionally, compromises were sought to avoid this sensor crosstalk and more recently, in particular in the operation of UUV platforms, survey sensor control routines have been developed.

Surveys requiring multiple high-resolution datasets typically require a compromise of mobilising separate survey vessels for each sensor (Parrott et al., 1999; McMullen et al., 2007). Conducting a survey of the same seafloor region for each of the interfering sensors is

uneconomical and inefficient. Evans et al. (Evans et al., 1999) investigated the advantages of single or dual vessel solutions for hydrographic surveys requiring multiple datasets of a region. The team concluded that although the dual vessel solution allowed the gathering of the multibeam data at higher survey speeds, the single vessel solution to conducting multibeam and sidescan sonar surveys proved more economical and improved the hydrographic analysis and understanding of the data. However, during the single vessel survey, the sidescan sonar deployed was of lower frequency (100kHz) to the sidescan sonar deployed during the dual vessel survey (300kHz), reducing the sidescan imagery resolution and data integrity.

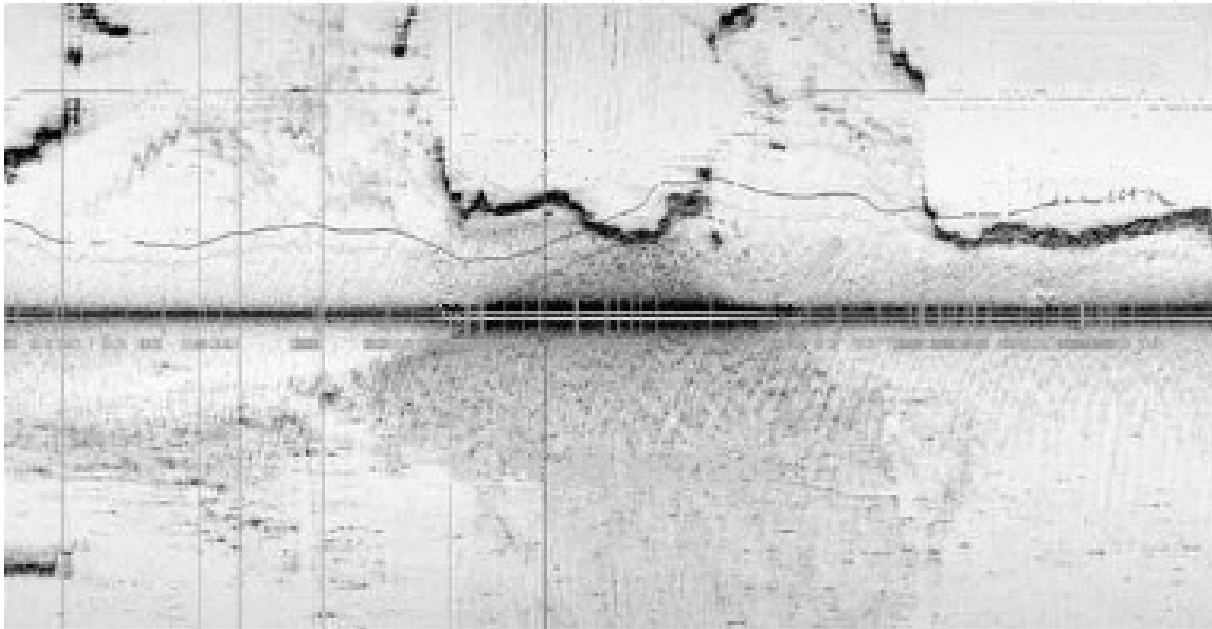


Fig. 2. Crosstalk can be seen on this sidescan sonar image where the backscatter is very low. The interference was caused from a simultaneously operating sonar.

Others have also attempted to avoid cross-sensor acoustic contamination by separating the operating frequency of the payload sonar sufficiently far that they are undetectable from one another (Pouliquen et al., 1999; Lurton & Le Gac, 2004). As a result, the sonar systems employed are a combination of high-frequency and low-frequency sonar. The low frequency systems significantly degrade the quality of the generated datasets, with the result that small-scale features may not be evident, thereby compromising the data interpretation process. An advanced solution must be utilised that will enable the simultaneous operation of high-frequency acoustic sensors to provide detailed datasets that are demanded by today's needs and standards.

Temporally separating the transmission-reception cycles of similar frequency sonar has been attempted in (de Moustier et al., 1990), which reports the concurrent acquisition of multibeam and sidescan sonar data using co-frequency 12kHz systems by interleaving their pings. The described algorithm takes into account the timing requirements of both systems and schedules the multibeam transmit cycles around the fixed sidescan timing events using a sound synchronisation unit. The sound synchronisation unit interleaves the transmission-reception cycle of each sensor, thus avoiding acoustic interference. However, because of the fixed transmission rates, the system is best suited for long-range, deep-water applications and does not provide optimal ping repetition rates.

Other triggering modules have been developed by a number of marine technology companies, such as GeoAcoustics' Timer2 module, to allow asynchronous triggering of multiple sonar systems while avoiding the effects of sensor crosstalk. Operator specified timing schedules are used to trigger the individual systems at fixed intervals. The interleaving of the otherwise interfering pulses avoids dataset contamination, enabling the simultaneous use of multiple high-frequency sonar sensors.

5. Remote payload control

The deployment of UUVs has, by their very nature, necessitated the development for remote payload sensor control routines. Typically, command and control of payload sensors are pre-programmed and/or operator based. C&C Technology's HUGIN 3000, a third generation AUV manufactured by Kongsberg Simrad, interfaces to the payload sensors through the HUGIN Payload Processor (Hagen & Kristensen, 2002). Survey specifications are programmed before deployment and take control of all sensor operations onboard. Another well-proven AUV, the Atlas Maridan's SeaOtter, enables the synchronised operation of multiple sensors by specifying the repetition rate, delay and duty cycle for each sensor during survey planning. The values are sent over the vehicle network to the Local Trigger Manager (LTM), which generates the signals required for each instrument during deployment (Ishoy, 2000). The Monterey Bay Aquarium Research Institute (MBARI) has developed the DORADO AUV, capable of conducting simultaneous multibeam bathymetry, sidescan sonar and sub-bottom surveys of an area of interest. The AUV is integrated with Reson's 7100 multibeam echosounder (200kHz), Edgetech's 110/410kHz chirp sidescan sonar and an Edgetech 2 - 16kHz chirp sub-bottom profiler. Simultaneous operation of the multiple sensors is managed by the Reson propriety timing algorithm. The multibeam echosounder acts as the master system, and along with the other integrated systems, is pinged using a fixed 1 pulse per second (PPS) clock, made available by the navigation system (Kirkwood, 2007).

Survey results have shown that the described systems have successfully completed surveys of an area of interest in which simultaneously operating sonar are deployed (George et al., 2002; Wernli, 2002; Kirkwood et al., 2004; Desa et al., 2006). However, the integrated systems do not allow for optimal surveys, leading to deficient datasets; the acoustic sensors used are not all of high-frequency and the payload control is pre-programmed and non-adaptable.

The intelligence of sensors is becoming increasingly sophisticated. Innovative developments in sensor technology have enabled the real-time data acquisition, processing and decision making based on the collected and processed data, of sensor systems during survey operations. Researchers at the Mobile and Marine Robotics Research Centre (MMRRC), University of Limerick, have developed an approach to the real-time adaptive control of multiple high-frequency sonar survey systems for UUVs (Thurman et al., 2008). This approach is based around a centralised sensor payload controller which manages the integrated sensors during survey missions, facilitating the operation of co-located, high-frequency sonar. The Multibeam is the master system and supplies the raw data to be processed in real-time to provide a priori bathymetry data to auxiliary acoustic sensors. The automated system is based on the interleaving of the sonar transmission-reception cycles to avoid issues of cross-sensor acoustic interference, permitting the integration of multiple acoustic sensors operating in parallel. By dynamically adapting the ping rates of the payload sensors, the system optimises the execution of the seabed mapping survey and improves the quality of the resulting data, thereby significantly increasing survey productivity.

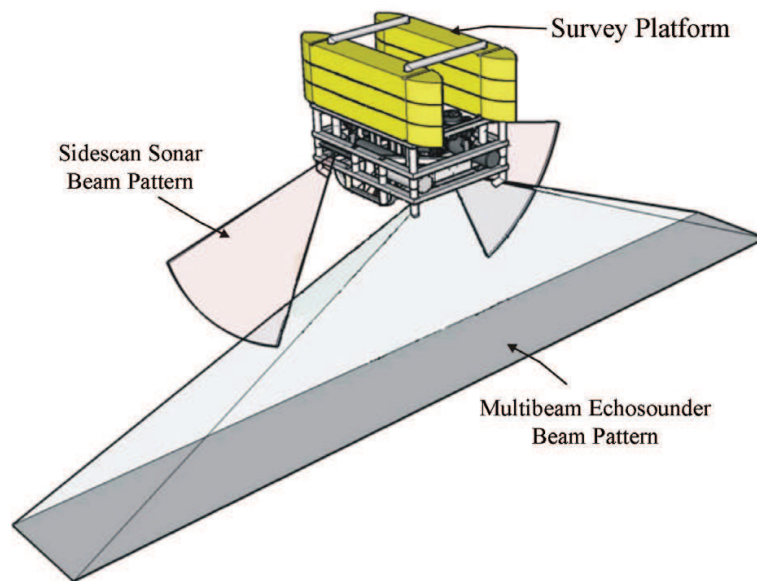


Fig. 3. System arrangement; the multibeam echosounder is mounted at the fore of the platform, with the sidescan sonar mounted in the rear, permitting the multibeam echosounder to provide a priori data to the controller.

6. Integrated acoustic controller system

Previously, multibeam bathymetric data was collected and stored during survey operations, with processing performed post-survey. However, recent advances in computational technology have enabled real-time processing of multibeam data. In-survey processing of the multibeam data allows time-critical survey control decisions to be made based on the assessment of real-time environmental information. The Integrated Acoustic Controller System utilises the modern computational resources and real-time processing techniques to enable synchronised multi-sonar operation through the prediction and temporal separation of each of the UUV's payload sonar's transmission-reception window.

Unlike traditional sensor triggering routines, which operate on fixed timing schedules, the system dynamically adapts the time separation between successive pings. The sensor triggering timing schedule is calculated as a function of each sensor's imaging geometry, the range between each sensor and the ensonified seafloor, the survey vessel velocity, and the desired resolution of the collected dataset. With the imaging geometry and mounting configuration of each instrument known, the required set of parameters is completed by analysis of the navigation and bathymetric data streams collected during the survey. The terrain-adaptive timing schedule enables optimal use of each sensor's available transmission-reception cycle windows; providing the capability to interleave the pings of multiple acoustic sensors, thus avoiding acoustic contamination while still adhering to high-resolution survey requirements.

The system exploits the fact that, due to the slow forward speed of the UUV platform, typically 2 - 4 knots, there occurs a high ping-to-ping coherence between successive multibeam swaths. This permits the duration of the next multibeam transmission-reception window to be predicted with a high degree of accuracy. The multibeam transducer is mounted to the fore of the survey platform such that the geometry of the region of the

seafloor to be interrogated by the sidescan sonar will already have been mapped, providing the a priori information needed to predict its transmission-reception window.

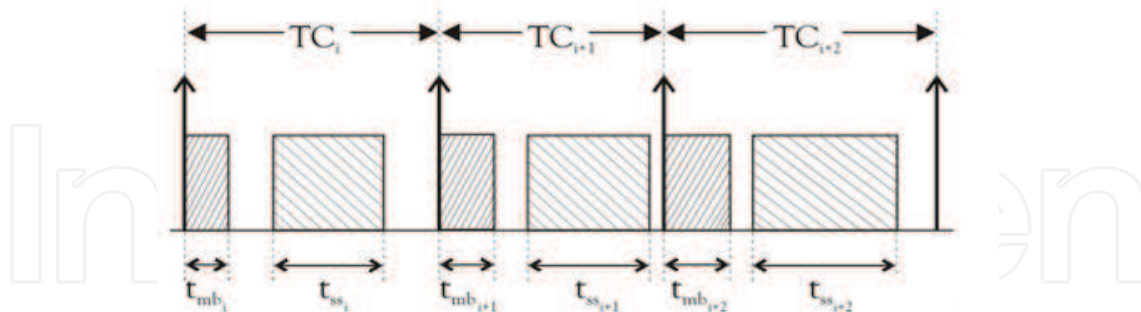


Fig. 4. Timing diagram of the Integrated Acoustic Controller System; within each Triggering Cycle, TC , the transmission-reception cycles of the multibeam echosounder, t_{mb} , and the sidescan sonar, t_{ss} , are scheduled. Separation of the transmit-receive windows enable the concurrent operation of the high-frequency sonar.

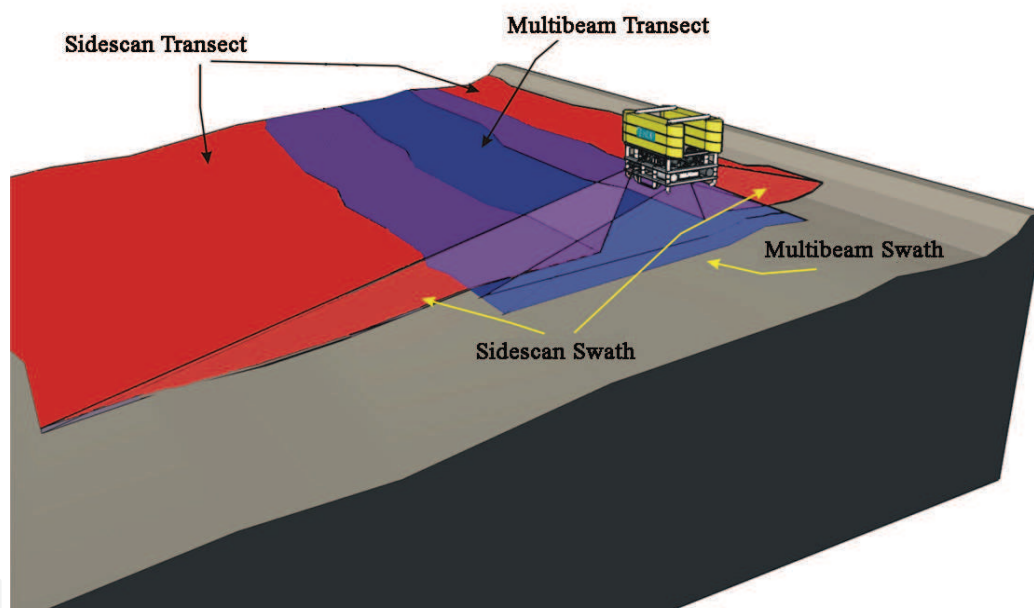


Fig. 5. Sonar transects during dual sonar operation.

The system is comprised of the multibeam sonar and data acquisition module, the sidescan sonar and data acquisition module, the position and orientation sensor and data acquisition module and the multi-sonar synchronisation module. The multibeam sonar system is the master system and provides to the survey controller the raw data that determines the multi-sensor triggering routine. The multibeam sonar data acquisition module reads in the raw seafloor data, filters for outliers and extracts each individual beam's time and angle couplet. In parallel, the navigational sensors provide concurrently generated high-frequency time-stamped Motion Reference Unit data, which is queued in the memory buffer. Both streams are fused by selecting the navigational message relating to the time-stamp encoded in the multibeam data. A transformation matrix is constructed and converts the body-fixed multibeam data to earth-fixed seafloor depth samples. A select number of geo-referenced depth points are then used to generate and populate a Digital Terrain Model (DTM) of the

surveyed region (in calculating the adaptive timing schedule it is not typically required to build a fully populated DTM, thereby reducing the processor's computational workload). By analysing the region of the DTM within the seafloor footprint of the payload sonar's reception beam the optimal ping rate of each individual sonar is calculated for each swath.

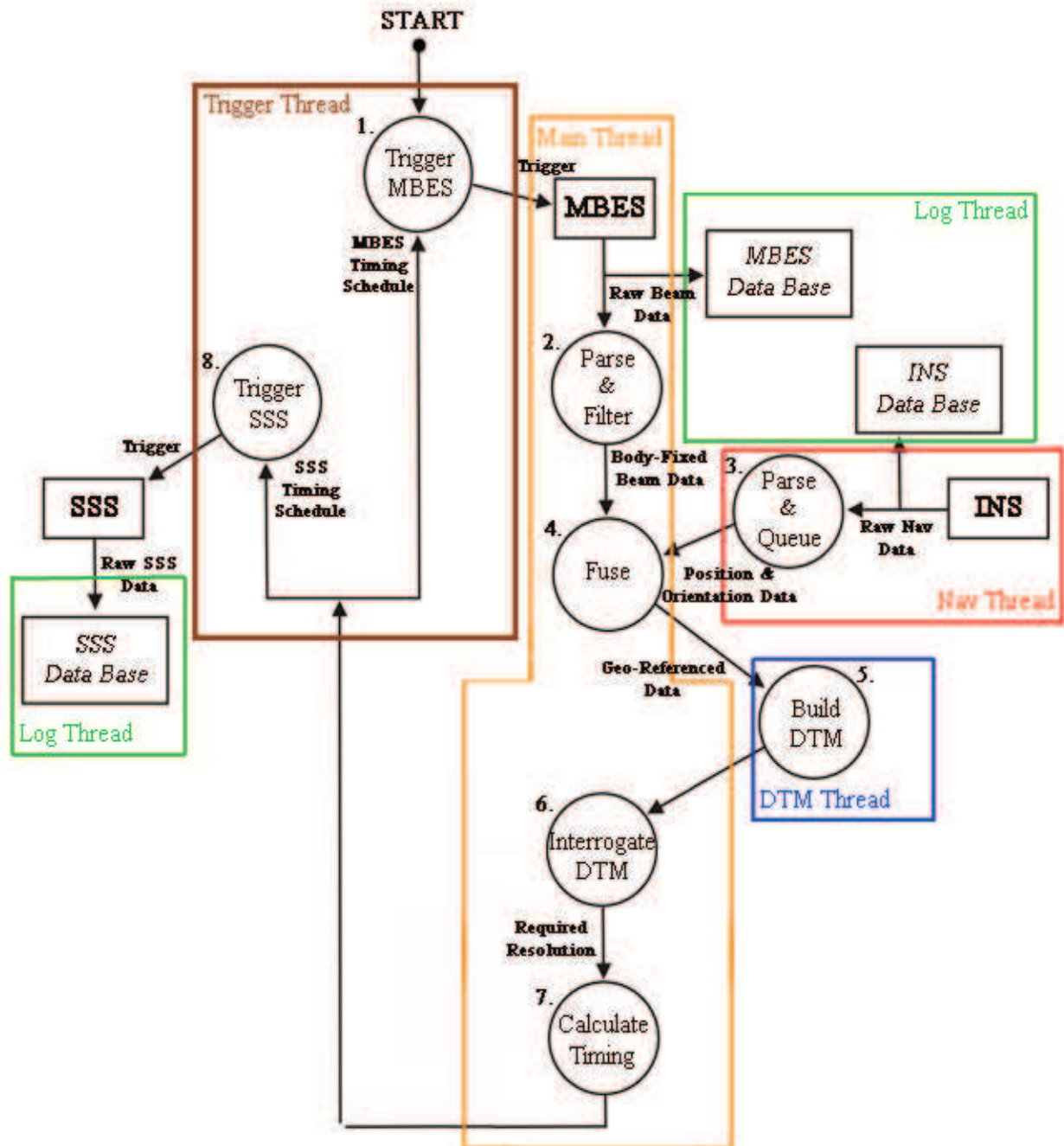


Fig. 6. Software architecture; the system is decomposed into a multi-threaded framework to enable independent modules to execute in parallel.

The system benefits are manifold and are of significant interest to the marine and off-shore communities:

- The system adapts to the varying geometry of the seafloor, optimising the use of the individual sensors.

- Survey productivity is increased due to the considerable reduction in survey duration and cost; the area of interest is surveyed, along with the supporting data being collected, only once.
- The simultaneous acquisition of multiple datasets improves the data interpretation process by allowing the combined analysis and interpretation of independent datasets of the same region.

The relative positional error between features evident in the datasets is also minimised, as the target region is encompassed by the instruments integrated on the same platform under the same environmental conditions and geo-referenced by the same navigational data, promoting the straightforward co-registration of the acoustic signature of features across multiple datasets.

7. Conclusion

Increased interest in the detailed exploration of our ocean seabeds has spurred the development and technological advancements in sonar technology. Sonar is an essential part of a modern marine survey system and has been successfully employed to record the composition, physical attributes, and habitat and community patterns of the seafloor. The integration of multiple sonar sensors into a marine survey suite allows for the simultaneous collection of individual datasets of the same seafloor region. A move towards multi-sensor integration is becoming more and more apparent in the marine industry, allowing for the enhancement of decision making and data analysis by exploiting the synergy in the information acquired from multiple sources.

However, the integration and concurrent operation of multiple sonar sensors in a marine survey suite creates issues of cross-sensor acoustic interference. The contamination caused by sensor crosstalk severely degrades the resulting datasets, and hence, the data examination and understanding. Traditionally, compromises were sought to avoid this sensor crosstalk by mobilising separate surveys for each of the interfering sensors or by separating the operating frequency of the sonar sufficiently far that they are undetectable from one another, and more recently, in particular in the operation of UUV platforms, survey sensor control routines have been developed. Nevertheless, solutions to the problem of sensor crosstalk remain inadequate and inefficient.

The intelligence of sensors is advancing rapidly. Innovative developments in sensor technology have enabled the data acquisition, processing and decision making to occur in real-time during survey operations. An approach to the real-time adaptive control of multiple high-frequency sonar systems was presented in this chapter. This approach is based around a centralised sensor payload controller which manages the integrated sensors during survey missions, facilitating the operation of co-located, high-frequency sonar. The multibeam is the master system and supplies the raw data to be processed in real-time to provide a priori bathymetry data to auxiliary acoustic sensors. The automated system is based on the interleaving of the sonar transmission-reception cycles in a non-interfering fashion.

By allowing real-time decision making to be made based on real-time mission data, the system optimises the execution of the seabed mapping survey and improves the quality of the resulting data, thereby significantly increasing survey productivity, and consequently, the data analysis and interpretation.

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The demand to explore the largest and also one of the richest parts of our planet, the advances in signal processing promoted by an exponential growth in computation power and a thorough study of sound propagation in the underwater realm, have led to remarkable advances in sonar technology in the last years. The work on hand is a sum of knowledge of several authors who contributed in various aspects of sonar technology. This book intends to give a broad overview of the advances in sonar technology of the last years that resulted from the research effort of the authors in both sonar systems and their applications. It is intended for scientist and engineers from a variety of backgrounds and even those that never had contact with sonar technology before will find an easy introduction with the topics and principles exposed here.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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