# Chapter 2
# Instrumentation and Data Acquisition System

Guidance and control of an autonomous vehicle requires measurement of its position and motion. To this end, the USV is equipped with instruments that include an Acoustic Doppler Current Profiler (ADCP), Inertial Measurement Unit (IMU), compass, tilt sensor, and Differential Global Positioning System (DGPS). The sensor outputs are either analog or digital, as well they differ within these formats. Thus, a data acquisition system is included aboard the USV to synchronously collect, decode, and process all data. A graphical programming language is used to develop the high-level modular program structure and perform some straightforward data processing while much of the complex processing is done with an imbedded low-level programming language. This strategy provides a software package that is quickly able to understand, modify, and transfer data while avoiding writing hardware specific drivers. Addition of imbedded low level programming provides efficiencies when needed. The first section in this chapter describes the instruments and details their performance and output, the second section overviews the data acquisition system and its layout, and the third section provides a high level description of the software.

## 2.1 The Sensors

### *2.1.1 Acoustic Doppler Current Profiler (ADCP)*

ADCPs use the Doppler effect to acoustically measure water velocity. They transmit sounds, in the form of acoustic pulses (pings), perpendicular to the transducer faces (the source and receivers) at a fixed frequency and record the echoes at discrete intervals of time (depth bins). The ping is reflected by scatterers moving with the water and the reflected signal is Doppler Shifted if the water has a relative velocity component parallel to the acoustic beam. Using four transducers pointed in different directions, each tilted at equal angles from the vertical axis of the ADCP and oriented in pairs that point in perpendicular planes, the ADCP computes the 3-Dimensional water velocity vector for each bin. All beams

C. Gelin: A Low-Cost, High Rate Motion Measurement System, NAMESS 1, pp. 7–18.
springerlink.com

**Fig. 4** Picture of an RDI Acoustic Doppler Current Profiler

measure the vertical water velocity component and each transducer pair measure the horizontal water velocity in its plane. In a similar manner, broadband ADCPs use phase to measure time dilation, instead of frequency changes, by measuring the change in arrival times from successive pulses. The ADCP also contains internal tilt and compass sensors to measure its orientation during a ping. However, these sensors are low quality and have poor response characteristics and are therefore not used in this application.

**Fig. 5** Diagram of transmission principle of an Acoustic Doppler Current Profiler, mounted onboard a ship, showing the 4 directions of the 4 beams

The 300 kHz RDI Broadband Workhorse ADCP (Figure 4) is mounted 45$^o$ counter-clockwise from its normal beam 3 forward orientation (Figure 6), so that beams 2 and 3 are looking ahead, and beams 1 and 4 are looking aft. In this configuration, all four beams detect similar magnitudes of Doppler shift in relation to surge and sway, which will aid in removing errors during post-processing (Figure 5).

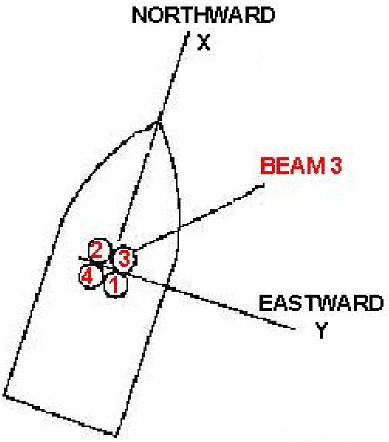

**Fig. 6** ADCP Beam orientation with beam 3 at 45 degrees with respect to the heading, looking from underneath the boat.

The RDI Workhorse Sentinel ADCP communicates at 115200 baud (selectable from 300 to 115200 baud) via RS232. Initialization of the ADCP requires a wake-up signal (at least 300 ms serial break) and downloading a mission command set. For this work, the type of ensemble output data structure selected is binary (real water-current data set), and the data rate is set to 1Hz (Table 1).

**Table 1** Specifications of the 300 KHz ADCP RDI Workhorse Sentinel

| PARAMETER | VALUE USED |
|---|---|
| RANGE | 126m (maximum) |
| CELL SIZE | 8m (maximum) |
| VELOCITY ACCURACY | ± 0.5 % of the water velocity relative to the ADCP ± 5 mm/s |
| VELOCITY RESOLUTION | 1 mm/s |
| VELOCITY RANGE | 5m/s (default) 20m/s (maximum) |
| NUMBER OF DEPTH CELLS | 1 – 128 |
| TILT | |
| RANGE | ±15° |
| ACCURACY | ±0.5° |
| PRECISION | ±0.5° |
| RESOLUTION | 0.01° |
| COMPASS | |
| ACCURACY | ±2° |
| PRECISION | ±0.5° |
| RESOLUTION | 0.01° |
| MAXIMUM TILT | ±15° |

The nature of the ADCP's acoustic method of measurement results in low repeatability between single measurements, single pings, of the same current. Thus, measurements are typically filtered with a moving average to decrease the standard deviation of the signal – the standard deviation of the relative velocity measured by the ADCP is function of the number of ping per average/ensemble and the size of the bins that are specified in the mission command set (Figure 7).

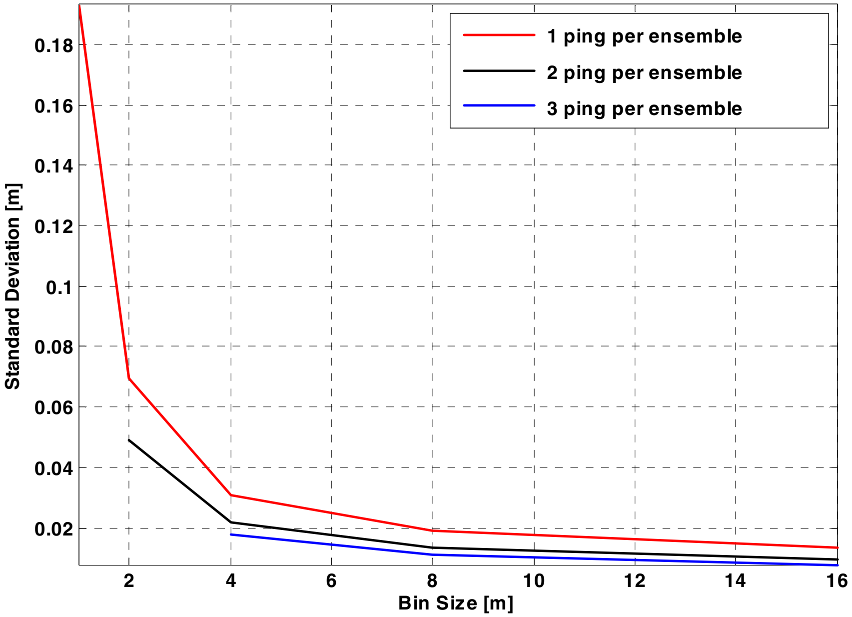

**Fig. 7** ADCP velocity standard deviation in function of the size of the bins and number of pings per ensemble chosen on the mission command set.

For this work, the single ping data is motion corrected and the variance of a single ping signal provides a basis to set the maximum level for the accuracy and precision of the vessel motion measurements. A value of less than 1 cm/s is desired for velocity measurements, which is about one half the value of the lowest single ping standard deviation (with an 8m bin size).

### *2.1.2 Inertial Measurement Unit IMU*

The low cost BEI Systron Donner Inertial Division MotionPak II contains three orthogonally mounted micromachined quartz angular rate gyroscopes and three silicon based accelerometers mounted in a compact, rugged package, with internal power regulation and signal conditioning electronics (Figure 8). The MotionPak accelerometers measure acceleration and rate gyroscopes measure angular velocity in three perpendicular directions. The sensor produces an output voltage that is proportional to the rate of rotation and acceleration sensed (Table 2).

**Fig. 8** BEI Inertial Measurement Unit Motion Pack II.

**Table 2** Specifications of the BEI Inertial Measurement Unit MotionPakII

| | RATE CHANNELS | | | ACCELERATION CHANNELS | | |
|---|---|---|---|---|---|---|
| PARAMETER | ANGULAR X-AXIS | ANGULAR Y-AXIS | ANGULAR Z-AXIS | LINEAR X-AXIS | LINEAR Y-AXIS | LINEAR Z-AXIS |
| RANGE | ± 75 °/s | | | ± 1.5 g | | |
| SCALE FACTOR | 0.133 V/°/s | | | 6.66 V/g | | |
| BIAS ERROR, MINIMUM | ± 5.0 °/s | | | ± 125 mg | | |
| INPUT AXIS ALIGNMENT | 1 ° typical | | | | | |

## *2.1.3 Compass TCM2*

The TCM2 compass module (Figure 9) is a biaxial inclinometer and a triaxial magnetometer. The biaxial inclinometer has no mechanical moving parts; instead it uses a fluid filled tilt sensor, which is an angle sensing device using gravity as a reference to measure the orientation of the compass. The TCM2 provides the heading while the roll and pitch angles from the internal tilt sensor do not have sufficient range to be useful and are only used as independent sensor measurements to check and verify the system performance (Table 3). The TCM2 communicates at 19200 baud via RS232, using the NMEA083 output protocol, the data are output at 8Hz.

**Fig. 9** TCM2-20 biaxial inclinometer and a triaxial magnetometer compass module

**Table 3** Specifications of the TCM2 biaxial inclinometer and a triaxial magnetometer compass module

| PARAMETER | HEADING INFORMATION | TILT INFORMATION |
|---|---|---|
| RANGE | | ± 20 ° |
| ACCURACY | when LEVEL: 0.5 ° RMS<br>when TILTED: 1.0 ° RMS | ± 0.2 ° |
| RESOLUTION | 0.1 ° | 0.1 ° |
| REPEATABILITY | ± 0.3 ° | |

## 2.1.4 Tilt Sensor

The tilt sensor is a Fredericks Company microprocessor based tilt sensor assembly (Figure 10). It is an accurate low power tilt sensor that allows sensor trim adjustments (Table 4). The sensor produces an output voltage from 0 to 5V that is proportional to the tilt perceived (± 60 degree angle range).

**Fig. 10** Fredericks Company ± 60 degree Angle Range tilt sensor

**Table 4** Specifications of the Fredericks Company ± 60 Degree Angle Range tilt sensor

| PARAMETER | TILT INFORMATION |
|---|---|
| RANGE | ± 60 ° |
| LINEAR RANGE | ± 25 ° |
| NULL VOLTAGE | ≤ 0.025 V |
| REPEATABILITY | 0.1 |
| RESOLUTION | ≤ 0.2 arc minutes |
| STABILITY @ 24 HRS | 0.1 |
| ANALOG OUTPUT RESOLUTION (0 TO 5V OUTPUT) | 1.5 mV |

### 2.1.5 Global Positioning System GPS

**Fig. 11** Diagrammatic repre-sentation of the 24 satellites of the Global Positioning System

**Fig. 12** Picture of the GARMIN Global Positioning System 76 receiver

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of 24 satellites (Figure 11). The GPS works 24 hours a day by transmitting a signal from the satellites to the Earth. GPS receivers use this signal to calculate the distance between the satellites known location and the receiver's antenna, then, using multiple satellites signals, it triangulates the user's geodetic location. The Garmin GPS 76 receiver is used in this work (Figure 12). In addition to conventional triangulation methods, the GPS 76 is designed to provide precise positioning using correction data obtained from the Wide Area Augmentation System (WAAS).

This unit uses a built-in quad helix antenna that can provide position accuracy to less than 3m when receiving WAAS corrections. The GARMIN GPS communicates at 4800 baud via RS232 using NMEA0183 format and the position data are output at 0.5Hz (Table 5).

**Table 5** Specifications of the GARMIN Global Positioning System 76 receiver

| PARAMETER | VALUE |
|---|---|
| **UPDATE RATE** | 0.5Hz, continuous |
| **GPS ACCURACY** | < 15 M (49 Ft) RMS 95% typical |
| **DGPS (USCG) ACCURACY** | 3-5 M (10-16 Ft), 95% typical |
| **DGPS WAAS ACCURACY** | 3 M (10 Ft), 95% typical with DGPS corrections |

## 2.2 Data Acquisition System

A data acquisition and processing system is developed to record the data from the sensors and process the data to calculate the motion and orientation of the vessel, in real-time, using a host-target framework of xPC Target (Figure 13).

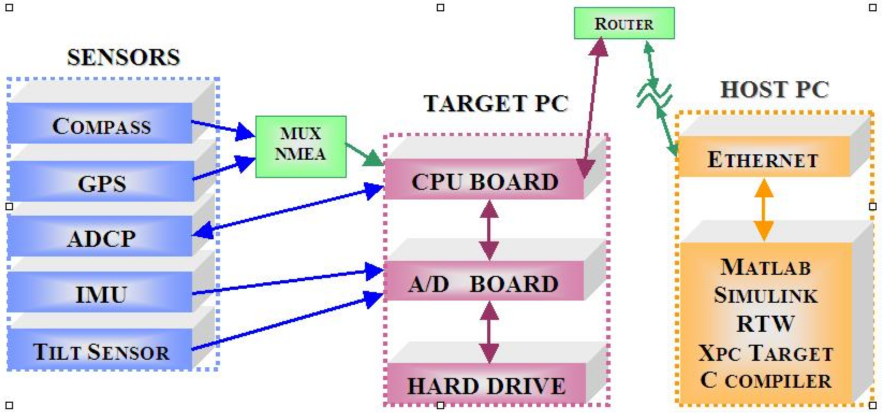

**Fig. 13** Overview of the data acquisition system, including the sensors, computers and links

### 2.2.1 Host Computer

The host computer can be any PC that runs a Microsoft Windows platform supported by MathWorks. It must contain a serial port or an Ethernet adapter card and operate MATLAB, Simulink, Real-Time Workshop, xPC Target, and a C compiler. The aim of the host PC is to control the target PC. Indeed, it can start, stop, monitor, and tune the application running on the target PC.

### 2.2.2 Target Computer

The USV is an open “wet” structure whose surface signature is to be minimized. Thus, to keep the visible and radar signature to a minimum while increasing the stability of the vessels, the electronics are packaged in a small pressure vessel that is located about 1m below the vessel water line. Since the instrumentation pressure case is small and the available power is limited, the selected onboard computer is of the PC104 format, which is compact and low power. The target computer is a “stack” of four or five cards that are used for data acquisition, processing, and storage. The computer is a MOPSlcd6 CPU board with a 166 MHz CPU and includes two serial ports, a parallel port, an Ethernet port, and a keyboard port. The computer and stack are powered with Direct Current to Direct current (DC/DC) converters that input the batteries unregulated 24 volts and output the needed regulated 5 volts.

Although only two serial ports are needed for this work, five serial ports are needed to communicate with the full instrument suite of the USV: 1) the GPS and the compass, 2) the ADCP, 3) the Dual Purpose Acoustic Modem (DAPM), 4) the High Performance Standard Node (HPSN), and 5) a command and control computer. Thus, a serial expansion board with four serial ports is used. The serial hub chosen is the Emerald-MM serial expansion board manufactured by Diamond

Systems. As the IMU and tilt sensor both output an analog signal, a Diamond-MM-32-AT AD/DA converter board is included in the PC104 stack and is configured with 32 single-ended channels. A Simpletec flash IDE 1 GB drive mounted on its controller board is used to store data. A VGA card can be installed when needed, to facilitate software debugging.

### 2.2.3 USV Hardware Layout

The instrumentation and data acquisition package consists of a central computer that is connected to five independent instruments, each of which has its own unique preprocessing equipment and data format (Figure 14). The MotionPack produces analog voltage signals that are filtered by a bank of DP68 Low-Pass Filters (Cutoff Frequency at 50Hz) prior to being input into the analog to digital converter and sampled at 128Hz. The tilt sensor is directly connects to the analog to digital converter with no prior filtering and sampled at 128Hz. Both the Garmin DGPS and the TCM2 compass output digital streams at the same baud rate that follow the RS-232 format and are encoded to meet the NMEA 0183 standard. As such, both signals are combined with a NM42 multiplexer from NoLand Engineering and input into the same serial port. The NM42 combines up to four NMEA 0183 instruments into a common output (Figure 15). This multiplexer reads and stores the incoming data from each instrument. Whenever a complete message is received, the multiplexer automatically dumps it to the outputs while it continues reading other input lines.

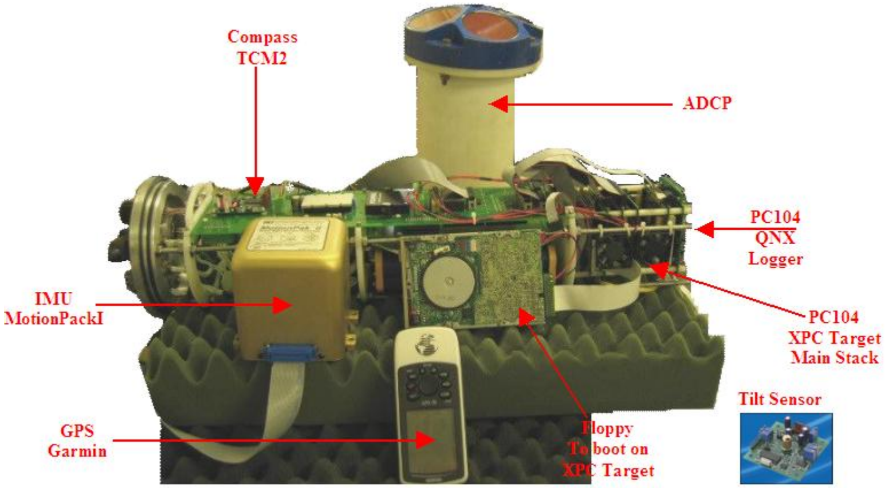

**Fig. 14** Picture of the acquisition setup

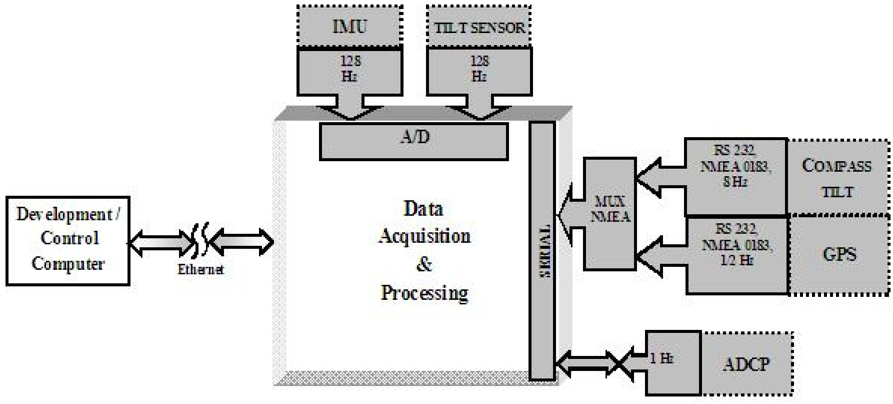

**Fig. 15** Block diagram of the acquisition hardware, including the sensors, computers and links

While the data flow from the IMU, GPS, tilt sensor, and the compass is one way, from the instrument to the data acquisition computer, data flow is bidirectional between the data acquisition system and the ADCP over a digital serial communication line. Unlike the other instruments which are independent from the data acquisition computer and output data continuously (analog) or at fixed rates (digital), the ADCP is programmed prior to sampling and is interrogated to trigger each sample. Thus, the ADCP requires a dedicated serial port and communicates at 115200 baud with a sample rate set to 1Hz.

### 2.2.4 Computer Networking

The communication between the host and the target computer is achieved with a Belkin 802.11g Wireless Cable/DSL Gateway Router connected to the target and with an 802.11g Wireless Notebook Network Card installed on the host computer (Figure 16). The Gateway Router uses the wireless 2.4 GHz signal and has a data rate up to 54 Mbps. It allows the host computer to start or stop the mission, reboot the target (PC104 stack), and monitor the application running on the target at distances up to 1800 feet.

**Fig. 16** Belkin 802.11g Wireless Cable/DSL Gateway Router and the 802.11g Wireless Notebook Network Card.

### 2.2.5 Software Overview

The acquisition software, Xpc Target, is a real-time graphical programming language that is based on a host-target configuration environment. This language was chosen because it provides a high level graphical development environment that rapidly enables the integration of software and hardware on PC-compatible hardware using visually organized functional blocks. Within these functional blocks, lower level graphical programming and embedded low level coding is done. As such, the software is developed on a PC, the host computer, which is separate from the data acquisition computer and contains all the individual development programs. In this work, the host computer includes MATLAB, Simulink, Real-Time Workshop, xPC Target interface blocks, and a C compiler. The software is compiled into a low-overhead executable file on the host computer and downloaded onto the target computer – the data acquisition computer. While the target computer is executing, the host computer is used to monitor the target and provide some level of data visualization (Figure 17).

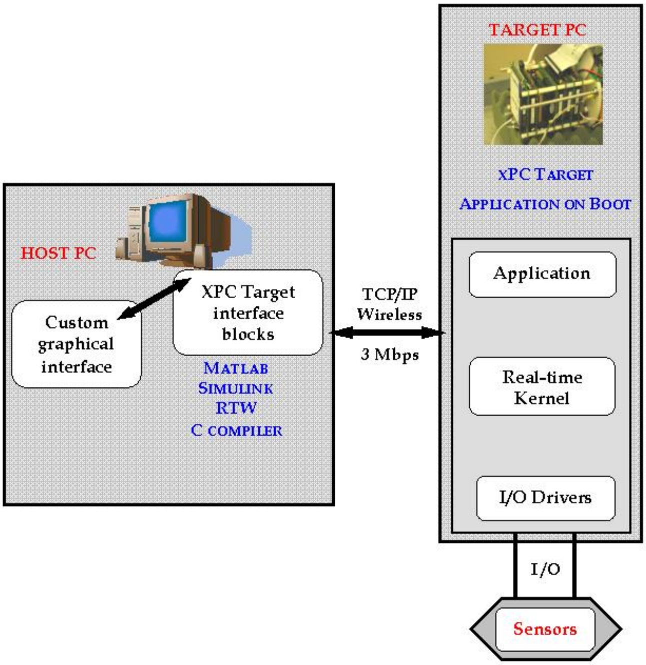

**Fig. 17** Block diagram of the links between the host PC, the target PC104 stack, the sensors, and Operating Systems of the entities

One guiding goal in the software development is that the program must be quickly and easily understandable and be developed in a framework that readily allows future modifications and additions without understanding of the program in its entirety. Thus, a modular approach is adopted that sees the software broken down into five key sections: 1) system initialization, 2) the data acquisition, translation and conversion; 3) rotational motion estimation; 4) translational motion estimation; and 5) ADCP signal decoding and correction. Each one of these main modules are themselves composed of sub-modules.