Chapter 6
Conclusion

Unmanned Surface Vehicles (USVs) are self contained unmanned untethered vessels that can transit on the surface of the water autonomously or through remote control. FAU has designed a multi-purpose oceanographic and GATEWAY USV that is a low cost mobile surface platform. Since standard GPS receivers are unable to provide the rate (0.5Hz) or precision required when used on a small vessel, a high rate (128Hz) and high precision position and orientation measurement system is developed. The system integrates a motion measurement package (the focus of this work) to aid in navigation, control, and enhances acoustic performance. The onboard sensors, including an Acoustic Doppler Current Profiler (ADCP), provide oceanographic measurements.

ADCPs measure the relative velocity between its sensor heads and the water using the Doppler shift and time dilation of an acoustic pulse. By transmitting acoustic pulses at a fixed frequency and listening to the Doppler shift of echoes returning from sound scatterers in the water, water velocity estimates can be made. While ADCPs non-intrusively measure water flow, they suffer from the inability to discriminate between motions in the water column and self-motion. When mounted on a moving platform, the measured velocity is the sum of the platform velocity and the water velocity. Thus, the vessel motion contamination needs to be removed to analyze the data and avoid long average times. The motion measurement system is used to control the ADCP by commanding it to ping at a set rate (1Hz) and decoding the measurements returned by the instrument. The single ping water velocity measurements are decoded, motion corrected, and converted into an earth fixed frame.

The motion measurement system of the USV consists of an Inertial Measurement Unit (IMU) with accelerometers and rate gyros, a GPS receiver, a flux-gate compass , a roll and tilt sensor, and an ADCP. While the sensors cannot be used independently to measure the position of the vehicle, they have complimentary characteristics that can be used to reduce or eliminate their individual errors when they are combined. Thus, integration and data fusion methods are used to combine the measurements from the sensors to estimate the position of the vehicle (Driscoll et al., 2000), in real-time. Using these techniques, a software package is developed where useful sensor measurements are preserved and erroneous data is rejected at all frequencies and the resulting, merged signal is drift free.

C. Gelin: A Low-Cost, High Rate Motion Measurement System, NAMESS 1, pp. 85–92.
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The data fusion techniques developed in this work combine the complementary outputs of sensors measuring a related state to eliminate the drift of integrating the measurement $\dot{x}_m(t)$, while increasing the rate and resolution of $x_m(t)$ where $x_m(t)$ and $\dot{x}_m(t)$ are measurements of some state $x(t)$ output by two distinct sensors (position sensor and velocity sensor for example). The pre-emphasized signal, $x_p(t)$, is obtained by summing the signal $x_m(t)$ with the derivative signal $\dot{x}_m(t)$, such that (Mudge and Lueck 1994):

$$x_p(t) = x_m(t) + \frac{1}{\Omega_c}\dot{x}_m(t)\ , \tag{38}$$

where the scaling factor Ω_c , denoting the cutoff frequency, is a real positive constant. The choice of Ω_c is determined by the characteristics of the complementary region of the two sensors. For frequencies that are small compared to the cutoff frequency ($\Omega \ll \Omega_c$), the signal portion of the spectrum comes predominantly from $x_m(t)$, while for $\Omega \gg \Omega_c$), the signal is predominately from $\dot{x}_m(t)$. The enhanced version $x_e(t)$ of the signal $x(t)$ is then obtained by convolving $x_p(t)$ with a single-pole, low-pass filter. The enhanced signal $x_e(t)$ of the signal $x(t)$ contains low-frequency information from the sensor measuring $x_m(t)$, and the high-frequency information from the sensor measuring $\dot{x}_m(t)$.

The first data fusion method is applied in finding the Euler angles. Considering the characteristics of each instrument, a data acquisition system is developed that synchronously decodes data from all the instruments and converts them into a consistent format using the Euler angles, which are not directly measured. The Euler angles, β, are obtained by fusing the low-frequency Euler angles, θ_L, and ϕ_L, calculated from the tilt measurements ξ and ζ, and the compass heading, ψ_L, with the high-frequency IMU angular rates, $\boldsymbol{w} \equiv [p, q, r]^{\mathrm{T}}$.

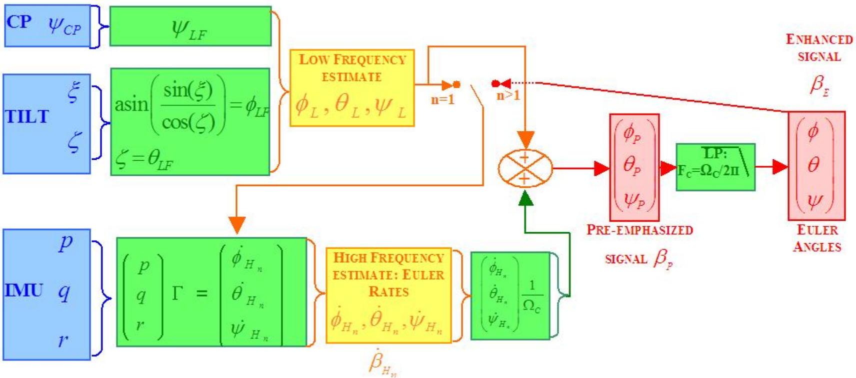

Fig. 84 Diagram of the data fusion IMU / TCM2/ Tilt sensor to obtain Euler angles, β.

The experiment applied to find a suitable data fusion frequency between the IMU, TCM2 and tilt sensor to calculate the Euler angles consists in mounting the sensors on the same rigid plate and turning the sensor system simultaneously about multiple axes and rotation at different speed. The IMU rate gyros are found to have a low drift rate and the data fusion point is chosen to be at 1/30Hz. This data fusion frequency is selected so that at frequencies lower than the cutoff frequency, the tilt sensors and compass heading, provide accurate and stable measures of the Euler angles, ϕ, θ and ψ and at frequencies above the cutoff frequency, the rate gyros in the IMU provide accurate measures of the Euler rates, $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$.

The estimated Euler angles are then used to convert the IMU acceleration from body-fixed frame, $\boldsymbol{a} \equiv [\dot{u}, \dot{v}, \dot{w}]^{\mathrm{T}}$, to the NED frame, $\boldsymbol{A} \equiv [\ddot{X}, \ddot{Y}, \ddot{Z}]^{\mathrm{T}}$, where gravity is removed. The enhanced velocity of the ship, $\boldsymbol{V}$, is obtained by directly fusing the high frequency (128Hz) acceleration measurement from the IMU, $\boldsymbol{A}$, and the low frequency (0.5Hz) velocity obtained from the speed and course overground output from the GPS, $\boldsymbol{V_{LF}^{GPS}} \equiv [V_{LF}^{X}, V_{LF}^{Y}, V_{LF}^{Z}]^{\mathrm{T}}$. The position is then obtained by fusing the enhanced velocity, $\boldsymbol{V} \equiv [V_X, V_Y, V_Z]^{\mathrm{T}}$, with the latitude and longitude measured with the GPS. Two experiments are conducted to choose the best data fusion point (Ω_C) to be later used to obtain the full frequency measure of the ships velocity, $\boldsymbol{V_E}$, and its position, $\boldsymbol{\eta_E}$.

The first experiment investigates the properties of the vertical NED acceleration and the different methods available to obtain the merged vertical velocity, $\boldsymbol{V_E^Z}$ and the merged position, Z_E. The experiment takes place in a machine shop and consists of mounting the IMU, the tilt sensor and the TCM2 compass on a level plate. The plate is leveled and tethered to the extremity of a 1.03m rigid lever. The middle of the lever is attached to a gearbox that is attached to a rotating engine. The extremity of the lever describes circular trajectories of 0.515m radius at different speeds. The test consists of six sets of vertical roundtrip periods of approximately 5, 10, 15, 20, 25 and 35 s, each lasting about 10 minutes. The speeds are manually set using the speed variator of the rotating engine.

The IMU, which is assumed accurate only at high frequencies, is merged with a null signal at low frequency and a data fusion point at 1/100Hz is found to be the best compromise to obtain a full frequency measure of the vertical velocity. The vertical velocity is then merge with a null signal to obtain the full frequency measure of the vertical position signal and a cutoff frequency of 1/50Hz is found to be the best choice for that data fusion method.

The second experiment investigates the properties of the data acquisition system on shore, without the ADCP in order to find the best data fusion points of the horizontal velocity and position signals. The experiments takes place in an open parking lot to ensure the GPS system has a clear and unimpeded signal. The experimental setup consists in mounting the IMU, the tilt sensor and the compass on a rigid plate that is fixed to a cart where the rest of the data acquisition system (without the ADCP) is mounted. Because of the lack of automatic motion control, the cart is moved manually between four spots on the ground that mark the corners of a square with 7.88m legs with the corners pointing towards the four cardinal points. Three trajectories are selected: a square path, a zigzag course and a circle. These trajectories are each repeated at least three times at different speeds. The path of the trajectories, speed and periodicity are selected to test the system's ability to accurately measure the cart motion.

The first data fusion process, involving the IMU acceleration and the GPS velocity measurement leads to a full frequency measure of the velocity measurement. Pre-filtering of IMU data are found to be necessary before the data fusion process (Figure 85) and the experiment observations suggest the complementary region of the sensors intersect around 0.05Hz, which is used as the data fusion point. This data fusion point is selected so that at frequencies lower than 0.05Hz the GPS provide an accurate measure of the velocity of the system, and at frequencies above 0.05Hz the IMU provides an accurate estimation of the velocity.

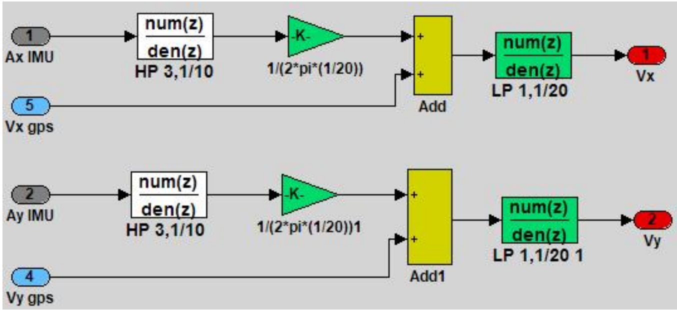

Fig. 85 Diagram of the data fusion between the IMU acceleration data and the DGPS velocity measurements in order to obtain the enhanced velocity estimate.

The subsequent data fusion process applied is between the merged velocity and the DGPS position measurement to obtain a full frequency measure of the position estimate. The choice of the data fusion frequency is done in a similar fashion to aforementioned and the same data fusion point at 0.05Hz is selected. Figure 86 shows the diagram of the process of the second data fusion process between the enhanced velocity signal and the DGPS position measurement.

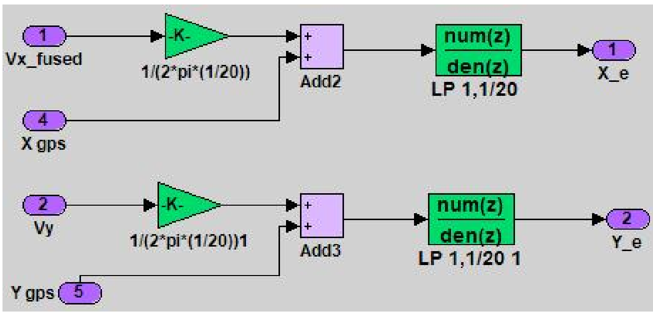

Fig. 86 Diagram of the data fusion process between the DGPS position measurement and the merged velocity estimate obtained by fusing the IMU acceleration data and the DGPS velocity.

The enhanced (merged) velocity signals estimated from the previously described first data fusion process have most of their significant spectral content below the data fusion point from the DGPS velocity data. Therefore, the DGPS position signal and the enhanced velocity signal have matching spectra, below the data fusion point, and no pre-processing is needed on the DGPS velocity signal before the data fusion with the DGPS position data.

Since the enhanced velocity signals are used to correct the ADCP unreferenced data it is important to quantify their standard deviation so that it is lower than the ADCP velocity standard deviation. 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).

Following the experiment conducted onshore, the standard deviation of the merged velocity error could have been determined by subtracting the expected velocity of the cart with the merged velocity estimate. However, since it was not possible to precisely control the motion of the cart, the expected velocity of the cart could not be determined. Instead, the estimation of the signals noise is applied by high-pass filtering the merged velocity signal, removing the motion of the vehicle, and computing the standard deviation of the filtered signal. Using this estimation process, the standard deviation of the merged velocity estimates (Table 15) is calculated for the three trajectories.

Table 15 Estimates of the standard deviation of the merged velocity signal for the three trajectories of the on shore data acquisition test.

Estimates of the merged velocity standard deviation [cm/s]	Square Path at 0.55m/s	Square Path at 0.93m/s	Square in zigzag course at 0.39m/s	Circle at 0.47m/s
NORTH COMPONENT	0.77	1.16	0.65	0.66
EAST COMPONENT	0.78	1.19	0.7	0.74

The standard deviation of the enhanced velocity signal averages 0.83 cm/s (< 1cm/s) and the signal is used for the correction of the ADCP data when performing a mission at sea. The mission at sea is conducted for the observation of the motion data acquisition system measurements in the field as well as the collection and correction of unreferenced ADCP data. Both the motion data acquisition system and TRDI ADCP are installed on a test vessel, the R/V Oceaneer IV, which performs a series of specifically chosen maneuvers in open sea while the motion data along with the ADCP data are simultaneously collected to be later post-processed. The mission is performed off the southeast coast of Florida where the currents run predominately near shore in a north-south direction with magnitudes ranging up to 1m/s. The ship maneuvers follows two different tracks: an L-shape track (going south then east) and a straight line roundtrip track along the south-north direction.

For this mission, the ADCP is a 600 kHz Teledyne RDI Broadband Workhorse Sentinel. Its reference beam, beam 3, is mounted 45^{o} counter-clockwise from the centerline of the ship in order to increase noise rejection and the effective ADCP measured velocity by a factor of 1.4. As a result, beams 2 and 3 are pointing forward, and beams 1 and 4 are pointing aft. The water profile will be composed of 16 bins, each 4m in length. A default blanking distance of 88cm is used in order to avoid measuring currents when the ADCP is ringing; resultantly the center of the first bin is located 5.05m away from the ADCP which puts the center of the last bin 65.05m away from the ADCP.

The first maneuver, L-shape track, is performed by heading south for 623.56m at approximately 1.04m/s and then east for 1274.8m at approximately 2.04m/s (according to the GPS measurements). The trajectory of the boat exhibits a slight drift to the east when heading south and a more noticeable drift to the north when heading east. This indicates the presence of a water current, as expected, mainly along shore in the south-north direction with a secondary transverse east component. The water currents' influence on the vessel's motion can also be observed during the second maneuver, where the straight line maneuver goes 687.6m south-east at approximately 1.07m/s, and then goes 1988m north-east at approximately 2.92m/s.

The water current is quantified when observing the corrected ADCP measurements. The correction of the ADCP data is performed in two different reference frames for comparison purposes. The first correction occurs in the ADCP radial beam coordinate frame, which allows us to manipulate ADCP data in its rawest form, i.e. no internal ADCP corrections applied. The second correction occurs in the North-East-Up Frame, the Earth coordinate frame of the ADCP. In addition to looking at the ADCP velocity profiles, the raw velocity at the first bin, where the water current is its strongest in the middle of the bin (~5m depth relative to the ADCP), is compared to the corrected ADCP velocity and the merged ship velocity. The estimates of the water current for the all missions are compiled in Table 16 and represented using Google earth in Figure 87.

Table 16 Summary of water current estimates obtain by correcting the ADCP data during the two maneuvers at sea.

<table>
<tr><th>Maneuver</th><th>Reference frame</th><th>Bin</th><th>Water current direction [°N]</th><th>Water current magnitude [m/s]</th></tr>
<tr><td rowspan="3">L-shape track going south then east</td><td rowspan="2">Beam</td><td>Bin 1</td><td>4.74° then 7.5°</td><td>0.5 then 0.72</td></tr>
<tr><td>All Bins</td><td>13° then 8.8°</td><td>0.72 then 0.64</td></tr>
<tr><td rowspan="3">Earth</td><td rowspan="2">Bin 1</td><td rowspan="2">8.6°</td><td rowspan="2">0.94</td></tr>
<tr><td rowspan="4">Straight line track going south then north</td></tr>
<tr><td>All Bins</td><td>5.3°</td><td>1.07</td></tr>
<tr><td rowspan="2">Beam</td><td>Bin 1</td><td>5.49° then 4.8°</td><td>0.65 then 0.68</td></tr>
<tr><td>All Bins</td><td>1.25° then 3.2°</td><td>0.64 then 0.67</td></tr>
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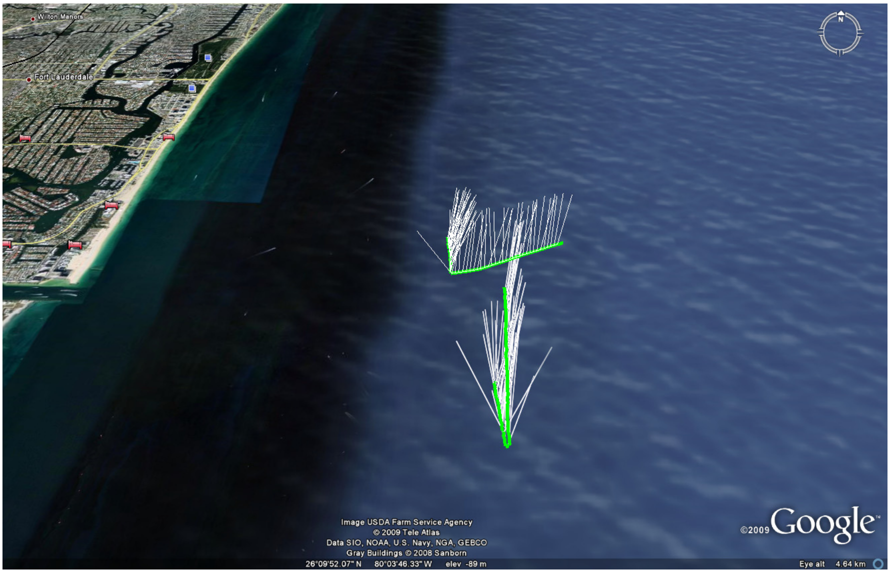

Fig. 87 Google Earth visualization of the mission at sea with the two maneuvers, first goes south-east then south-north

The correction of the ADCP data can occur accurately since the standard deviation of the enhanced velocity of the ship (0.83 cm/s) is lower than the standard deviation of the water current measurement from the ADCP (Table 15).

Table 17 Estimated standard deviation of the ADCP velocity during the first and second maneuver at sea in correlation to the bin size, using the standard deviation of the error velocity

1st Maneuver	Estimated standard deviation of the ADCP measured corrected current velocity [cm/s]
Bin 1-4 : 4 to 20 m	2.6
Bin 5-8 : 20 to 36 m	3.3
Bin 9-12 : 36 to 52 m	4.4
2nd Maneuver	
Bin 1-4 : 4 to 20 m	2.4
Bin 5-8 : 20 to 36 m	3
Bin 9-12 : 36 to 52 m	3.75

This book has presented a low-cost, high rate motion measurement system developed for an unmanned surface vehicle with underwater navigation and oceanographic applications. The system integrates a motion measurement package to aid in navigation and control while correcting data from an Acoustic Doppler Current Profiler (ADCP), providing oceanographic measurements.

Recommendations

Another test at sea as well as a complete calibration of the data acquisition system are the first two recommendations. An integration of the system for different control system is also preferable as well as a formal design method for the data fusion process so we can determine the optimal filter shape. Finally a fuzzification of the data fusion process is suggested.