IMU for Vessel and Offshore Piping Survey

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Abstract “The Inertial Measurement Unit (IMU) is an electronic unit which records angular velocity and linear acceleration data which is fed into a central processing unit for data interpreting and logging. The unit constitutes of two independent sensors. The first sensor is the 3-axis gyroscope and second sensor is the 3-axis accelerometer. The IMU should also have a data interpreter that can draw the track it went through. This should enable the engineers to calculate the co-ordinates, based on longitude and latitude measures. To improve the effectiveness of the device, the device could possibly be designed to transfer the data wirelessly using Bluetooth technology to the nearby data logging machine, which can simultaneously calculate the algorithms to figure the correct of the vessel piping system.

Keywords IMU, Shipboard, Piping, Gyroscope, Accelerometer

1. Introduction

In modern day naval architecture, ships are designed to be very smooth skewed shapes to give them the ability to propel and maneuver at the least resistance, in order to maximize the propulsive efficiency. Therefore it has been a norm for many years to design a vessel with the storage tanks on the side of skin, or what we call as side-shell. In the process of vessel design, it is an unavoidable thing to not design curved wing tanks and deep tanks, for different type of liquid storage.

Due to the skewed shape of the vessel geometry the access to those tanks are really difficult. And the Code of Regulations requires that there should be vent pipes for all independent, fixed, non-pressure pipes tanks. But for the construction and repairing necessities over the years these piping system has to be properly located and physically accessed.

As already mentioned, access to the shape of the vessel can cause extremely difficulty for the engineers to gain access to the tanks and therefore locate the piping system. In order to do that, Professor Brandon Taravella of the Naval Architecture and Marine Engineering department from University of New Orleans has brought up the proposal to investigate this certain problem affecting the shipbuilding industry. In order to solve this issue, research was conducted to find a unique solution that can record the routing of a complicated piping system.

Co-relation between IMU and Ship's Degrees of Freedom:

To begin the investigation, we employed the idea of inertial measurement units (IMU) that can record the track path of all kinds of piping system. For a complicated system inside a vessel, we needed multiple units, which should give us several data even for extreme remote locations. One example of such IMU device is InvenSense MPU-6050 which uses motion interface. This use of motion interface can interact with the other devices by tracking motion in free space and delivering the data as an input to the data interpreter. [1]

The six degree of freedom (DOF) of MPU-6050 can expressed in terms of the naval architectural nomenclature. They are:

Heave, Pitch, Roll, Sway, Surge, Yaw

Figure 1. A ship's 6 DOF

Application of IMU is not new in the shipbuilding industry. IMU units are being used by several companies for heave compensation applications for ships under operations. In further development, the inertial measurement units (IMU) can be comprised of analog-digital converters (ADC), a microcontroller (CPU) and inertial measurement system (IMS) which can transform the co-ordinates based on a relative origin.

2. System Architecture

The key advantages of using MPU-6050 is the device can be operated within a very small package size, at low power consumption, high accuracy and repeatability, high shock tolerance and programmed based on the requirement of the application. Therefore dropping or running the IMU through the long pipes at high velocity is not risky. [2] Also MPU-6050 can support configurable features such as gesture recognition, panning and zooming, scrolling, tap detection and shake detection.

The MPU 6050 consists of Digital Motion Processor (DMP) which includes both the gyroscope and the accelerometer. The DMP can sensor timing synchronization and gesture detection. The algorithms inside the IMU can perform over run-time bias and compass calibration. This device can also be programmed with temperature sensor reading so that different liquids flowing through the different pipes can be easily detected. [1]

Figure 2. MPU 6050 representation of 6-DOF

There are certain features that make the IMU suitable for such applications. To list the capabilities the controller inside the IMU features [3]:

- Two-axis stabilized
- Overcurrent protection
- Thermal protection
- Under voltage protection
- Wrong polarity protection

In order to suit the IMU for the purpose of measuring the complicated piping system of a ship, a calibration of the axis and validation of the accuracy of the hardware is essential. Considering the acceleration, the unit would continuously compute the following equation of motion relative to the earth's axis:

$$a_G = a_T + \dot{\vec{\Omega}} \times \vec{r} + \vec{\Omega} \times (\vec{\Omega} \times \vec{r}) + 2\vec{\Omega} \times \dot{\vec{r}} + a_{rel}$$

Figure 3. Geometric representation of the IMU orientation related to the earth axis

The following illustration represents how the equation is executed within the accelerometer:

As the IMU travels through the pipes, the gyroscope within the accelerometer constantly records the orientation of the device. This would allow to record the changes in direction and pathways of the pipe. The gyroscope in combination with the accelerometers gives the ability to the IMU for an enormous direction- and motion-sensing.

The global co-ordinate frame is defined by gravity and the geomagnetic field. The local co-ordinate frame is expressed by the rotation about the global axes. [8]

[global quaternion, local quaternion, local euler, global acceleration]
 $\{ G_{qw} \ G_{qx} \ G_{qy} \ G_{qz} \ L_{qw} \ L_{qx} \ L_{qy} \ L_{qz} \ r_x \ r_y \ r_z \ l_{ax} \ l_{ay} \ l_{az} \}$

The domain of the magnetometer, accelerometer and gyroscope is defined as:

[accelerometer, magnetometer, gyroscope]
 $\{ a_x \ a_y \ a_z \ m_x \ m_y \ m_z \ g_x \ g_y \ g_z \}$

A recent journal article was published by the mechanical engineering department of University of Michigan examining the IMU functionality inside a baseball. A highly miniaturized wireless transmitter was attached to the IMU hardware. The entire unit was about a size of a quarter and provided accurate three axis sensing of acceleration and angular velocity. The IMU had 8Mbytes of memory attached to it which could later be connected to a computer for the data analysis. [4]

Based on the experiment, the researchers were able to publish data for the travel path of different balls, with different angular and linear velocity.

Figure 4. Image Courtesy: A Highly Miniaturized, Wireless Inertial Measurement Unit for Characterizing the Dynamics of Pitched Baseballs and Softballs- Ryan S. McGinnis and Noel C. Perkins)

In similar manner, the IMU unit designed for the shipboard piping system can be made to travel at high velocity within the pipe bends by the help of vacuum.

A typical section of a ship structure can be very complicated. With all the structures, engineers usually bend the pipes to fit the inner hull with the least possible interference. Therefore each piping system, such like bilge, ballast, sounding pipes, etc., needs to have pre-construction schematic and routing diagram. Different schedule pipes should be taken into consideration, given that the IMU hardware has to have an unrestrained movement. Also pump locations are important because IMU hardware, if fed into pump propeller, can cause significant damage.

Different Scenarios:

Considering other IMU besides MPU 6050, a recent literature published by The Institution of Engineering and Technology [5] has proposed to use ultra-tight integration, based on the vector tracking, for IMU's travelling at high speed. The ultra-tight integration can compensate for the Doppler shift, giving more accurate reading for the travel

path and more accurate data reducing the number of false results from the IMUs. Another company came up with wireless miniature IMU for dynamic position tracking. This miniature unit can re-adjust magnetic field reference, since earth magnetic field can be distorted by metal or electromagnetic sources such like the hull of the ship. The unit is especially helpful where the battery is rechargeable and can run for up to ten hours without recharging. [6]

Figure 5. Complicated piping system of a vessel

In order to get the IMU pass through the piping at high velocity, the hardware unit can be cushioned with foam or highly heat compensating elastic material. Keeping in mind that pipes usually contains liquids, an airtight and waterproof capsule can be a good option to insulate the hardware from possible damages. The pathway for the IMU unit can be as simple as it is shown:

Figure 6. Pathway taken by the IMU

Considering many utilization of IMU technology, Northrop Grumman introduces inertial fiber-optic gyro for space application named LN-200 (15). This IMU utilizes fiber optic gyros, radar stabilization, data transfer to user equipment with the help of digital serial bus. The scientific research of the device discussed in this paper also envisions to improve the IMU tracking device to be equipped with fiber optic gyros, stabilizer and low noise MEM technology. This would enable the device to broaden its use in military, air-force and naval applications. Also the future research would like to integrate low-energy consuming battery or power source, ensuring a longer usage hours. In future the IMU device may also include an error checking option using the MHD sensor, a sensor that utilizes the magnetometer, using the behavior of fluid interaction and its relation to the magnetic field.

3. Experimental Method

To simplify the experiment and effectively record the data a very sensitive but readily available device was used during the experimentation. A commercially available smartphone that uses IMU to co-ordinate with the device movement, position and orientation has been used to record the data and time frame. The device was dropped from several known

heights, while an application known as “DataCollection” developed by Christopher Wozny recorded acceleration, gyroscopic and magnetometer data.

Data Collection:

Sample Magnetic Data Recorded

Table 1. Raw Magnetic Orientation Data

Time(sec)	TYPE	rx	ry	rz	correction	POLAR CO-ORDINATES
0.1	MAGNETO	68.202056	-49.294922	143.478516	-360.5672	397.0847517
0.2	MAGNETO	68.301566	-50.671875	143.203125	-361.996887	398.4741197
0.3	MAGNETO	68.40149	-49.845703	146.232422	-362.282806	399.7450571
0.4	MAGNETO	68.501436	-49.845703	144.029297	-359.9953	396.8854939
0.6	MAGNETO	68.701545	-47.917969	143.753906	-353.990601	391.1400838
0.7	MAGNETO	68.801384	-48.193359	142.376953	-351.989075	388.8749619
0.8	MAGNETO	68.901842	-45.439453	142.927734	-341.123413	378.9534638
0.9	MAGNETO	69.001564	-48.744141	144.029297	-343.982788	382.3686754
1	MAGNETO	69.101485	-46.816406	144.855469	-343.125	381.6866039
1.1	MAGNETO	69.20149	-46.541016	146.232422	-342.267181	381.4258209
1.2	MAGNETO	69.301374	-40.482422	143.478516	-342.267181	379.7030612
1.3	MAGNETO	69.401401	-40.482422	144.580078	-342.83905	380.6539033
1.4	MAGNETO	69.501539	-38.003906	143.753906	-339.121887	376.7540319
1.5	MAGNETO	69.601657	-44.0625	144.304688	-341.409363	379.6973672
1.6	MAGNETO	69.701944	-42.685547	146.232422	-341.123413	380.0388415
1.7	MAGNETO	69.801539	-41.308594	144.855469	-337.978119	376.5514183
1.8	MAGNETO	69.901349	-42.410156	144.855469	-340.265625	378.7461186
1.9	MAGNETO	70.00142	-45.164062	143.203125	-340.837494	378.9687634
2	MAGNETO	70.101439	-42.960938	144.855469	-336.834351	375.7663381
2.1	MAGNETO	70.200783	-42.960938	144.304688	-340.837494	379.1672882
2.2	MAGNETO	70.301361	-44.0625	143.753906	-343.696869	381.6759208
2.3	MAGNETO	70.401552	-40.757812	144.855469	-344.268738	382.2586148
2.4	MAGNETO	70.501376	-38.554688	144.855469	-348.271851	385.6595611
2.5	MAGNETO	70.60145	-37.728516	146.232422	-347.985931	385.8576617
2.6	MAGNETO	70.701375	-33.597656	144.304688	-349.987488	386.5780279
2.7	MAGNETO	70.801396	-34.148438	145.957031	-352.274994	389.332865
2.8	MAGNETO	70.901392	-30.292969	145.957031	-349.987488	386.9617139
2.9	MAGNETO	71.001359	-29.466797	148.986328	-346.270325	384.7200918
3	MAGNETO	71.101579	-29.466797	147.884766	-346.842163	384.8286849

Figure 7. Raw data of Magnetic orientation recorded over a time period of 10.00sec

A rotation about the Z axis, the Y axis or the X axis can be respectively described by a rotation matrix $R(\psi)$, $R(\theta)$, $R(\phi)$, represented as following[11]

$$R_z(\psi) = \begin{pmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R_y(\theta) = \begin{pmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

$$R_x(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix}$$

The earth's magnetic field can be expressed as

$$B_d = R_x(\phi) \cdot R_y(\theta) \cdot R_z(\psi) \cdot g_r$$

where,

$$\phi = \arctan2\left(\frac{g_{dy}}{g_{dz}}\right) \text{ and}$$

$$\theta = \arctan\left(-\frac{g_{dx}}{g_{dy} \cdot \sin(\phi) + g_{dz} \cdot \cos(\phi)}\right)$$

thus the yaw angle can be computed as :

$$\psi = \arctan2\left(\frac{B_{dx} \cdot \sin(\phi) - B_{dy} \cdot \cos(\phi)}{B_{dx} \cdot \cos(\theta) + B_{dy} \cdot \sin(\phi) \cdot \sin(\theta) + B_{dz} \cdot \sin(\theta) \cdot \cos(\phi)}\right)$$

Sample Attitude Data Recorded

Table 2. Raw Attitude Data

Time(sec)	Type	sx	sy	sz	Error Correction Factor	Path
0.1	ATTITUDE	68.2011	41.94169	7.640745	165.836	80.42933
0.2	ATTITUDE	68.30103	42.49074	7.70151	165.6191	80.80722
0.3	ATTITUDE	68.40107	43.2191	7.992622	165.3977	81.30485
0.4	ATTITUDE	68.50104	44.01197	8.546804	165.0776	81.86876
0.5	ATTITUDE	68.60103	45.57906	7.875237	165.2284	82.73797
0.6	ATTITUDE	68.70111	50.45467	4.987447	164.9167	85.38378
0.7	ATTITUDE	68.80101	55.84766	1.065572	165.0378	88.62096
0.8	ATTITUDE	68.90098	63.00094	-0.62247	162.2695	93.36408
0.9	ATTITUDE	69.00111	66.75767	0.597862	159.2173	96.01092
1	ATTITUDE	69.10109	66.90104	5.844283	153.2799	96.35801
1.1	ATTITUDE	69.20102	67.19265	10.48429	147.2604	97.02347
1.2	ATTITUDE	69.30098	65.27968	14.14434	144.041	96.25032
1.3	ATTITUDE	69.40102	64.90123	19.25221	139.3948	96.95009
1.4	ATTITUDE	69.50112	67.02292	27.05239	132.4404	100.2712
1.5	ATTITUDE	69.60127	67.74294	28.13908	132.1196	101.12
1.6	ATTITUDE	69.70133	67.37363	25.61815	133.5289	100.2685
1.7	ATTITUDE	69.80106	67.72675	26.44433	132.3881	100.7889
1.8	ATTITUDE	69.90099	69.40429	22.25932	135.2934	100.988
1.9	ATTITUDE	70.001	70.73888	23.0037	135.3206	102.1435
2	ATTITUDE	70.10081	70.61021	24.85609	133.4844	102.5561
2.1	ATTITUDE	70.2001	70.35778	22.65919	134.2603	101.9397
2.2	ATTITUDE	70.30098	72.45841	11.9999	139.3311	101.6683
2.3	ATTITUDE	70.40106	70.62062	3.825249	137.7068	99.79085
2.4	ATTITUDE	70.50095	67.7084	6.946391	124.8216	97.99522
2.5	ATTITUDE	70.60106	66.77612	9.922646	120.3969	97.68326
2.6	ATTITUDE	70.70101	66.56321	10.56764	115.8955	97.67788
2.7	ATTITUDE	70.80101	65.99468	4.919901	112.2923	96.91381
2.8	ATTITUDE	70.90101	68.28716	4.116206	110.7499	98.52427
2.9	ATTITUDE	71.001	72.46886	2.607612	109.2425	101.4873
3	ATTITUDE	71.10121	76.64315	4.660504	105.036	104.6483

Figure 8. Raw data of Attitude recorded over a time period of 10.00sec

The gyrometer inside the IMU is being modelled by:

$$\bar{\Omega} = \Omega + b + \eta$$

where Ω the true value, b is the slowly time-varying bias and η zero mean noise. This is electronic sub-structure of the IMU, but what it represents is the raw estimates of the roll ϕ and pitch θ . The attitude matrix can be written as [12]:

$$R = \begin{bmatrix} C\theta C\psi & S\phi S\theta C\psi - C\phi S\psi & C\phi S\theta C\psi + S\phi S\psi \\ C\theta S\psi & S\phi S\theta S\psi + C\phi C\psi & C\phi S\theta S\psi - S\phi C\psi \\ -S\theta & S\phi C\theta & C\phi C\theta \end{bmatrix}$$

Sample Acceleration Data Recorded

Table 3. Raw Acceleration Data

Time(sec)	TYPE	Raw Data from Experiment				Linear Acceleration
0.1	ACCEL	68.201423	-0.077179	0.742584	0.729187	68.20940698
0.2	ACCEL	68.301302	-0.098236	0.738174	0.701935	68.30896807
0.3	ACCEL	68.40127	-0.079544	0.738617	0.714432	68.40903473
0.4	ACCEL	68.501221	-0.065781	0.799011	0.727478	68.50977484
0.5	ACCEL	68.601215	0.012573	1.064148	0.701248	68.61305282
0.6	ACCEL	68.70133	-0.026138	1.201385	0.559265	68.71411449
0.7	ACCEL	68.801177	0.040619	1.177307	0.761612	68.81547581
0.8	ACCEL	68.901213	-0.095367	0.969162	0.505508	68.90994893
0.9	ACCEL	69.001338	-0.120056	0.752563	0.496567	69.00733286
1	ACCEL	69.101274	-0.130173	0.701294	0.594147	69.10750927
1.1	ACCEL	69.201266	-0.053894	0.771225	0.425812	69.20689434
1.2	ACCEL	69.301158	-0.045563	0.772491	0.459427	69.30700103
1.3	ACCEL	69.401187	-0.153748	0.79039	0.438293	69.40724179
1.4	ACCEL	69.501316	-0.23616	0.842422	0.304642	69.50749009
1.5	ACCEL	69.601443	-0.10704	0.885269	0.402679	69.60831974
1.6	ACCEL	69.701653	-0.152649	0.873413	0.33728	69.70810814
1.7	ACCEL	69.801279	-0.218872	0.878693	0.316971	69.80787224
1.8	ACCEL	69.901144	-0.070511	0.926254	0.235764	69.9077137
1.9	ACCEL	70.001203	-0.069946	0.92717	0.221115	70.00772707
2	ACCEL	70.100968	-0.187088	0.934341	0.230972	70.10782451
2.1	ACCEL	70.200295	-0.157394	1.011261	0.463699	70.20928611
2.2	ACCEL	70.301143	-0.065491	0.953339	0.188919	70.30789104
2.3	ACCEL	70.401221	-0.038544	0.837036	0.296112	70.40683003
2.4	ACCEL	70.501162	-0.009872	0.928497	0.535568	70.50931059
2.5	ACCEL	70.601232	-0.056625	0.964066	0.467026	70.60938112
2.6	ACCEL	70.701168	-0.099945	0.870132	0.463669	70.70811314
2.7	ACCEL	70.801181	-0.022995	0.92009	0.422592	70.808424
2.8	ACCEL	70.901183	-0.043747	0.915497	0.335678	70.90790139
2.9	ACCEL	71.001152	-0.019897	0.966232	0.280701	71.00828387
3	ACCEL	71.101375	-0.015305	0.959152	0.155731	71.10801633

Figure 9. Raw data of Linear Acceleration recorded over a time period of 10.00sec

The acceleration resulting from the IMU can be calculated as:

$$\hat{a} = \Omega \times (\Omega \times \rho r)$$

Where Ω is the angular rate and ρ is the turn radius and r is unit vector from the center of turning. Linear acceleration in the three dimensions are the average of the acceleration

accumulated from the surface of a cube.[13] Given by the equation, the average acceleration is:

$$\vec{a} = (a_x, a_y, a_z) = \left(\frac{a_{x1} + a_{x2}}{2}, \frac{a_{y1} + a_{y2}}{2}, \frac{a_{z1} + a_{z2}}{2} \right)$$

Considering the rotation, the acceleration changes to,

$$\vec{a} = (a_{dx}, a_{dy}, a_{dz}) = \left(\frac{a_{x2} - a_{x1}}{2}, \frac{a_{y2} - a_{y1}}{2}, \frac{a_{z2} - a_{z1}}{2} \right)$$

But we need the angular acceleration normalized with unit radius,

$$\vec{a}_{zxy} = \left(\frac{a_{dx}}{r}, \frac{a_{dy}}{r}, \frac{a_{dz}}{r} \right)$$

$$\vec{\omega}_{zxy}(t) = \vec{\omega}_{zxy}(t - \Delta t) + \vec{a}_{zxy}(\Delta t)$$

$$\vec{\theta}_{zxy}(t) = \vec{\theta}_{zxy}(t - \Delta t) + \omega_{zxy}(\Delta t)$$

representing angular acceleration along Z,X,Y axes as $\vec{a}_z, \vec{a}_y, \vec{a}_x$ on XY, YZ, and ZX plane.

Sample Gyroscopic Data Recorded

Table 4. Raw Gyroscope Data

Time	TYPE	Raw Data from Experiment			
0.1	GYRO	68.201553	-0.007944	-0.002394	-0.008751
0.2	GYRO	68.301413	-0.001288	-0.014124	-0.045426
0.3	GYRO	68.401382	0.003758	0.061948	-0.052688
0.4	GYRO	68.501329	0.047002	-0.048925	-0.003953
0.5	GYRO	68.601328	0.531739	-0.36349	0.111419
0.6	GYRO	68.701442	1.126556	-0.614649	0.037606
0.7	GYRO	68.801282	1.598032	-0.507508	-0.238727
0.8	GYRO	68.901709	1.060218	-0.528968	-0.313446
0.9	GYRO	69.001456	0.122029	0.411756	-0.436814
1	GYRO	69.101383	-0.041032	-0.064252	-0.516182
1.1	GYRO	69.201387	-0.273649	0.098875	-0.255871
1.2	GYRO	69.30127	-0.278631	0.222968	-0.208122
1.3	GYRO	69.401298	0.615041	0.27739	-0.348275
1.4	GYRO	69.50143	0.212098	0.299285	-0.080371
1.5	GYRO	69.601552	-0.371234	-0.21913	0.192479
1.6	GYRO	69.701778	0.034247	-0.264539	-0.148994
1.7	GYRO	69.801396	0.086377	-0.103364	0.215259
1.8	GYRO	69.901251	0.33867	0.086264	0.220372
1.9	GYRO	70.001317	-0.029066	0.027871	-0.04231
2	GYRO	70.101182	0.014204	-0.203762	-0.133451
2.1	GYRO	70.200535	0.143788	-0.744097	0.3551
2.2	GYRO	70.301255	0.131176	-1.429203	0.054245
2.3	GYRO	70.401379	-0.796534	-2.948191	-0.824675
2.4	GYRO	70.501273	-0.429378	0.146411	-0.067616
2.5	GYRO	70.601343	0.112498	-0.251937	-0.537601
2.6	GYRO	70.701273	-0.43301	-1.536566	-0.232054
2.7	GYRO	70.801288	0.363717	-0.476707	0.072429
2.8	GYRO	70.90129	0.55788	-0.467455	0.142628
2.9	GYRO	71.001258	0.67702	-0.286937	-0.0157
3	GYRO	71.101482	0.475449	-0.478554	0.042794

Figure 10. Raw data of Gyroscope recorded over a time period of 10.00sec

4. Conclusions

This idea still has a lot of potential to grow. The shipbuilding industry has lot more complications which could be solved by using such simple and cost-effective IMU units. Using inexpensive computer programming codes and the IMU raw data from the device, the shipyard and construction engineers can conduct very practical and cost effective piping surveys. The development of such a device has the applicability in military sectors and law enforcement. Such devices can be used to identify hidden paths/tracks, retrieve information of underground inaccessible places and can be modified to suit specific to US Navy, Army and Marines. Not only military, but commercial oil and gas industry in the deep water horizon can also benefit from such a technology. Survey, construction, pipeline laying in deep sea, LNG, petrochemical industries could potentially expand the use IMU technology to fit their uses. More research would result in better simplification of the hardware unit, thus further improvement can excel the technology towards the benefit of engineering and scientific sectors.

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