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Analysis of Real-Time Velocity Compensation for Outdoor Optical Mouse Sensor Odometry

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***Abstract*—This paper investigates the linearity of optical flow odometry with respect to velocity when using refocused optical mouse sensors for outdoor robotic navigation. Optical mouse sensors are small, inexpensive and contactless devices which include a low resolution CMOS camera, DSP hardware and optical flow firmware to provide optical displacement measurements in two dimensions. We perform experiments using different velocities, sampling periods and with decoupled acceleration to develop a linear, real-time compensation algorithm providing velocity corrected displacement measurements.**

***Index Terms*—Robotic Navigation, Optical mouse, Optical Flow**

I. Introduction

The classic approach to robotic dead-reckoning navigation is through the use of wheel encoders; typically optical or hall effects sensors are used allowing the robot to measure the rotation of each wheel to infer how far it has moved. Wheel rotation is an imperfect measurement technique as the odometry measurements are based on contact with the ground surface, which exhibits differing amounts of slippage over different surfaces. This slippage, leads to an accumulation of errors in the odometry measurements[4].

Several researchers are experimenting with using optical mouse sensors as an alternate method of dead-reckoning navigation[3], [5], [6], [8], [9], [10], [11], [12], [13]. Optical mouse sensors integrate a low-resolution camera (in the order of 18x18 pixels), some DSP hardware and proprietary firmware containing optical flow algorithms to infer displacement in both X and Y directions based on the flow of features identified in successive image frames[1]. These sensors are inexpensive, physically small and have frame rates in the order of 1500 frames per second. Since optical mouse sensors are inherently non-contact devices they possess a definitive advantage over traditional wheel encoders as they are decoupled from the various kinematic forces which result in accumulated errors due to wheel slippage over different surfaces.

The remainder of this article is organised as follows: Section II commences with an investigation into the current research being performed in optical mouse odometry. In Section III we describe the experimental technique used to analyse the effects of different velocities with respect to displacement for optical mouse sensors in outdoor robotics. Section IV then presents and discusses the data obtained through the testing, resulting in a compensation algorithm which scales displacement measurements based on the velocity, a concept which is then concluded in Section V.

II. Previous Work

Researchers investigating the use of optical mouse sensors for robotic odometry have identified several sources of error including: height displacement (above the measurement surface), type of surface, angular orientation, lighting conditions along with velocity and acceleration[9], [11], [14]. Of these sources of error, height displacement is particularly significant resulting in most research performing odometry measurements over smooth indoor surfaces which the sensor can make direct contact with and in several cases whilst still mounted in a mouse body. Surfaces with significant discontinuities, such as the gaps between tiles, have been shown to introduce additional errors due to the variation in height displacement[11].

For outdoor robotic odometry it is impractical to have a sensor or lens in direct contact with the ground (rough terrain is far more likely to scratch or displace the lens). Further, outdoor surfaces tend to be less smooth and so have significantly more discontinuities compared to the smoother indoor surfaces. Several researchers showing promising results have fitted new lenses to increase the factory prescribed 7.35mm focal length to something in the order of centimetres, which allows the sensor to be mounted a further distance from the measurement surface enabling outdoor odometry[12], [7]. One positive development shown was that as the focal length of the sensors is increased, they become less sensitive to their height displacement over ground, a positive finding which lends these sensors well to outdoor robotic odometery.

In our previous paper [12] we proposed and tested a system using pairs of optical mouse sensors with a focal length of 32mm over an asphalt concrete road surface using a robotic gantry shown in Figure 1. Using several sensors and SQUAL (a count of significant features being tracked) as a measure of certainty weighting variable we showed how optical mouse sensors could be useful for outdoor robotic navigation. Experiments for that paper were conducted at a constant velocity; a variable which we experimentally characterise in this paper.

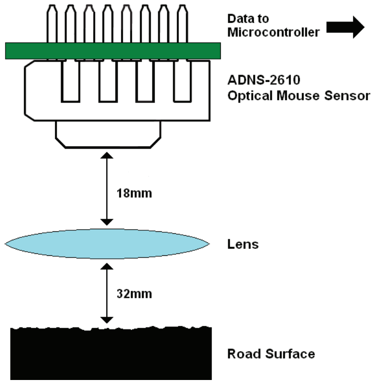

Fig. 1. Refocused optical mouse sensor with focal length of 32mm

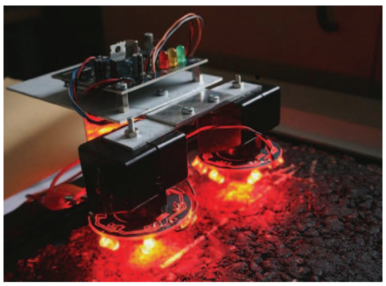

Fig. 2. Experimental test setup with two optical mouse sensors on gantry mounted above road surface

III. Experimental Testing

A total of four different experiments were carried out with each providing data for a different insight into optical mouse odometry stability over different velocity ranges. The experiments were performed on a computer controlled robotic gantry and with a block of asphalt concrete (typical road surface) as the surface under test which was illuminated by a ring of 628nm LEDs as shown in Figure 2. An ADNS-2610 optical mouse sensor was coupled with a new lens giving it a focal length of 32mm (shown in Figure 1) and a measurement window size of 2mmx2mm. The optical mouse sensor was interfaced with an Atmel microcontroller and transmitted data wirelessly back to a computer.

Experiment 1 involved moving the optical mouse sensor back and forth along a 150mm stretch of road in one dimension as the displacement measurements from the sensor were sampled and recorded. A fixed 20ms sampling period was used and the velocity was increased from 2cm/s up to 25cm/s in the smallest velocity increments (which are non-linear) allowed by the robotic gantry. The test was repeated 10 times for each different velocity and average displacement values for different velocities were calculated. The purpose of this experiment is to provide a baseline level of odometry performance including both acceleration and deceleration effects.

Experiment 2 excluded the effects due to acceleration and deceleration using a break-beam laser sensor to capture displacement data for a 45mm segment of the 150mm that the sensor was moved over. A fixed 20ms sampling period was used and the velocity was increased using the same procedure as in Experiment 1.

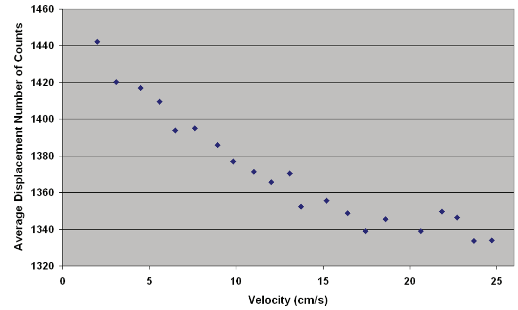

Fig. 3. Results from Experiment 1 showing an increased displacement measured as the velocity is decreased

Experiment 3 aimed to test if their was a link between the rate the optical mouse sensor was sampled and the velocity that the sensor was moving at. The sensor was repeatedly moved back and forth over a 150mm sample of road surface. The sampling period was incrementally increased from 10ms up to 200ms. For each sampling period a range of velocities were incrementally tested and the displacement measurements from the mouse sensor were recorded and repeated 10 times for each velocity and sampling period combination.

Experiment 4 was formulated to see if a correction transform could be applied to data as it was sampled to counteract any inaccuracies due to different velocities. The sensor was repeatedly moved over a 150mm road surface and the raw values sampled by the sensor were recorded. A fixed sampling period of 20ms was used and the velocity was tested with the same values used in Experiment 3.

Results from these four experiments enable us to determine how different velocities effect the displacement measurements from optical mouse sensors and if necessary correct for any systematic errors.

IV. Experimental Results and Discussion

The results from Experiment 1, as shown in Figure 3, indicate a definite trend between the velocity that the sensor is traveling at and the displacement that it measures. For slower velocities (2cm/s) the sensor measures displacements over 8% higher than results obtained for travelling at higher velocities (25cm/s).

Experiment 2 was formulated to see if the measured changes in displacement were somehow due to the effects of acceleration and deceleration; specifically if the lower acceleration and deceleration present with the lower velocities was causing higher displacement measurements as observed in Experiment 1. The results from this experiment is shown in Figure 4, which reflects a similar trend to the results compiled for Experiment 1. Since the results follow a similar trend it is reasonable to conclude that the increased displacement measured at lower velocities isn't caused by the acceleration and deceleration effects for the different velocities used.

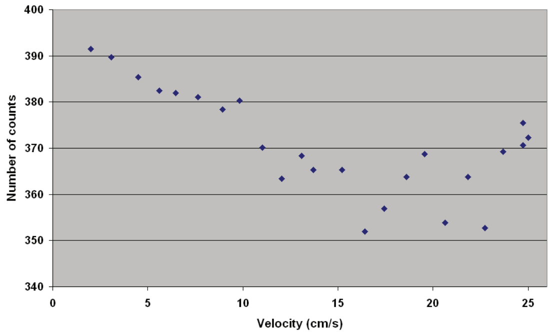

Fig. 4. Results from Experiment 2 demonstrate that acceleration effects are not the cause of increased displacement measurements at low velocities

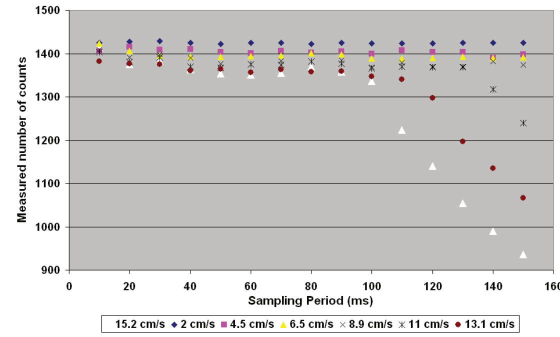

Fig. 5. Results for Experiment 3 show different sampling periods have little effect on the measured displacement

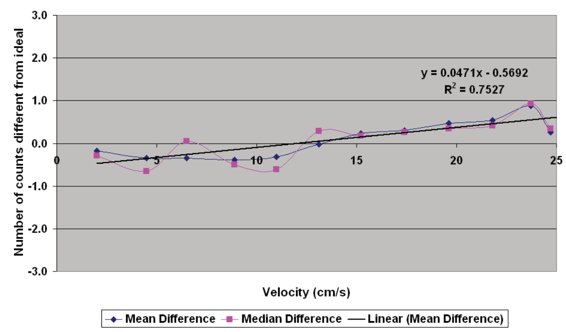

Fig. 6. Experiment 4 results show difference between actual raw sensor sampled data and theoretically calculated values for a resolution of 235 CPI

The average standard deviation for the number of counts for Experiment 1 was 6.8, but when the break-beam laser setup was used in Experiment 2 the average standard deviation was reduced to 3.8 (a reduction of 44%). Therefore from Experiment 2 it can be concluded that the effects due to acceleration and deceleration add additional noise to the data; markedly from the vibration induced into the system when accelerating or decelerating when using higher velocities.

In Experiment 3 we wanted to investigate the stability of the displacement sensor over a range of different sampling periods. Figure 5 shows the different velocities measured for Experiment 3 are clearly segmented into horizontal bands suggesting that the measured displacement is largely unaffected by the sampling interval. These horizontal bands have relatively low standard deviations calculated over different sampling intervals. A standard deviation of 1.7 was measured when moving at 2cm/s ranging through to a standard deviation of 11.2 when moving at 8.9 cm/s. For higher velocities with large sampling periods unusually low displacements have been recorded. These lower readings were because the sampling period was too high, allowing registers in the optical mouse sensor to overflow. Since there is little change induced by the sampling period, a fixed sampling interval lower than SI_{MAX} from Equation 1 once the maximum velocity (V_{MAX}) and counts per inch (CPI) are determined.

$$SI_{MAX} = \frac{2^7}{(CPI \times V_{MAX})} \tag{1}$$

We can deduce from Experiments 1 and 3 there appears to be an intrinsic scaling of displacement measurements based on the velocity of the optical mouse sensor. In Experiment 4 we have recorded the actual values being recorded each time the sensor is sampled and have taken a mean and median for each different velocity tested. An expected sensor value was calculated for each velocity based on the number of expected counts for a resolution of 235 CPI (counts per inch), the current velocity and a fixed sample period of 20ms. The sampled values were then subtracted from the expected ideal value and are displayed in Figure 6 along with their mean and median difference.

The optical mouse sensors only return integer numbers and so we would expect the median (though it is the most common number returned by the sensor) to be non-ideal as it has no fractional component which is present when we calculate an expected count based on the current velocity. Hence a linear best fit line was applied to the mean plot with R^2 = 0.75, showing it to be a good fit. This linearisation of velocity dependance can thus be used to determine a corrected value in real time.

$$\Delta U_{R/L,x/y,i}(mm) = K(1.0214 C_{R/L,x/y,i} - 0.4748) \tag{2}$$

Assuming a differential drive vehicle with optical mouse sensors positioned on both left and right sides, a first order correction algorithm (Equation 2) has been developed, which is applied to each new incremental value sampled by each of the sensors ($C_{R/L,i}$) for both X any Y vectors. This algorithm linearly scales the sensor data as established from Experiment 4 using the linear fit shown in Figure 8 and also converts sampled values into millimetres based on a calibration factor K, which is both height and surface dependent as expected from [12]. For the particular asphalt concrete surface at a lens height of 32mm above the ground we have calculated K = 150/1390 = 0.115, corresponding to a resolution of 235 CPI (compared to the factory lens setup which has a resolution of 400 CPI).

Having converted the sensor data into incremental vectorised distances travelled for each sensor, equations 3-6, as

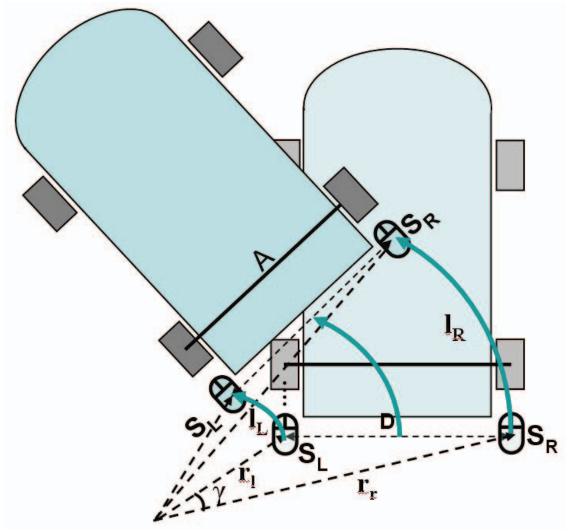

Fig. 7. Robot pose computed using arcs of sensor pair measurements

developed in [3] and [12] with reference to a dual sensor navigation system shown in Fig. 7, can be used to compute the robots change in pose ($\Delta\theta$) and position (ΔX and ΔY). Where, $L_{L(R)}$ corresponds to the radii of the arc for the left (right) sensor calculated using the cosine rule.

$$\Delta\theta = \frac{\sqrt{l_L^2 + l_R^2 - 2cos(\gamma)l_L l_R}}{D}.sgn(\overline{y}_R - \overline{y}_L) \tag{3}$$

Having computed the radii of each arc, the mean radii for a pair of sensors (U) can be computed as:

$$U = \frac{l_R + l_L}{2} \tag{4}$$

Finally the change in position, as specified in Cartesian coordinates, can be computed where θ_i refers to the new pose (a sum of the pose and the change in pose from 3) when using a fixed velocity.

$$\Delta X = Ucos(\theta_i) \tag{5}$$

$$\Delta Y = Usin(\theta_i) \tag{6}$$

For a more robust multi-sensor design, equations 3-6 can be aggregated into matrixes and cross correlated to remove spurious or noisy sensor readings as shown in[12].

The velocities used for these experiments vary from 2cm/s to 25cm/s, with both lower and upper limits imposed by the robotic gantry test setup. Further experimentation using a higher velocity robotic gantry would be of interest, particularly to demonstrate at what point the linearity of sampled measurements breaks down. The manufacturers quote a maximum velocity of 12in/s (corresponding to 30.5cm/s which is marginally faster than our tests)[1]. Having raised and refocused the optical mouse sensor, the measurement window size has been increased from 1.1mm x 1.1mm to 2mm x 2mm. As a consequence of this increase in window measurement size we would expect a ratiometric increase to the maximum velocity to something in the order of 21in/s (54cm/s); a velocity which should be adequate for many small robotics applications. The maximum velocity could be increased by further enlarging the window size; an increase which would come at a sacrifice of resolution or possibly through investigation into refocussing laser based optical mouse sensors which have resolutions of up to 5000cpi and maximum velocities of 150in/s [2].

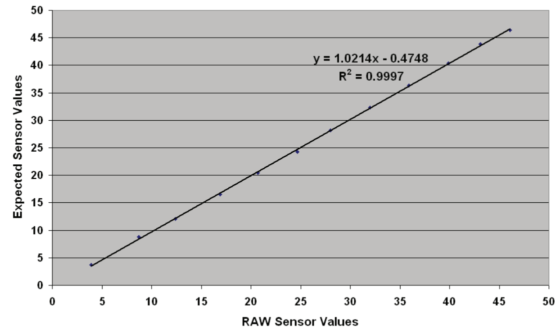

Fig. 8. Expected sensor values (for different velocities) with a 20ms sampling interval plotted against the actual values read from the sensor

Several researchers have suggested that several optical mouse sensors are required provide reliable odometry, reducing measurement errors via sensor correlation and SQUAL scaling[11], [6], [12]. For such sensor arrays the resolution for each sensor would need to be independently calibrated as this calibration is dependent on the height above ground as well as the precise lens setup. Performing this calibration would lead to different K values for each sensor which should provide a more reliable multi-sensor odometry platform.

V. Conclusion

In this paper we have experimentally investigated the effect of velocity on optical mouse measurements for outdoor robotic odometry over an asphalt concrete road surface. It was observed that the velocity that the sensor was moving at had an impact on the displacement measured of up to 8% when travelling at slower velocities.

Decoupling acceleration and deceleration effects resulted in a 44% reduced standard deviation, but with the same trend of lower velocities resulting a higher measured displacement. A range of different sampling periods were also trialled which demonstrated that provided the sampling period is sufficiently small with respect to the velocity, the sampling period has little effect on the measured displacement, and hence a fixed sampling period is sufficient.

A first order, linear correction algorithm was developed which operates at real-time on data as it is sampled, providing both velocity compensated scaling and a conversion to millimetres based on the new 235 CPI calculated resolution of the sensors when positioned at 32mm above the target surface. Using this simple linear first order correction it is envisaged that once calibrated, an array of sensors could be used to provide odometry information for outdoor mobile robots to providing a reliable, kinematic independent dead-reckoning navigation system.

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