Low cost 3D obstacle perception and tactile sensor for Micro and Macro robots (under review)

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Abstract—Many sensors like the laser range finder, stereo vision cameras, etc. which help in building the robots perception of the world around it in 3D including the obstacles etc are very costly. In this paper I present the design, construction and working prototypes of few sensors built low cost which I believe would help in bringing down the cost of sensory equipment used in both micro and macro robots. The usage of these sensors in this paper is shown using Snake robots. The sensors are built using components off the shelf. One set of sensors built uses structured infrared light projection and another sensor uses capacitive sensing. A comparison with today’s commercially available sensors is done, few applications are shown and other possible uses are discussed. I believe these low cost sensors would help revolutionize both research in robotics as well as the associated commercial applications.

I. INTRODUCTION

If a Snake robot has to be used in a search and rescue where the terrain is uneven, rugged and one needs to know the immediate terrain ahead of the robot one needs to have some sort of a feedback. The feedback can be about the terrain immediately the Snake robot is in contact with and the terrain ahead. Thus I explored the possibility of making a low cost 3D sensor for Snake robots. Sensors like Sharp IR, Ultrasonic sound sensors, Laser range finders, stereo vision camera, time of flight cameras etc are being used from quite a long time in both mobile and modular robots to get range information and thus help the robot in knowing about its immediate surroundings. An infrared range finder sends out a light pulse and gets bounced of the obstacle. Based on obstacles position and the angle of reflection the distance of obstacle is decided using triangulation. But an infrared sensor has a non-linear response and gives information about only one point in the environment. Some signal conditioning and calibration is required to get more accurate range information. In this Snake robot “S7” by Dr.Gavin miller [1] a combination of Infrared and Ultrasonic distance sensors is used. A rotating IR is used on the head to get the points in plane perpendicular to the axis of rotation. The resolution of this scan line depends on the angular resolution of the servo driving the IR sensor, the distance of the obstacle and the maximum possible range measurable by the sensors. Also it takes some time to perform a single horizontal sweep to get the scan. A 3D point cloud can be obtained by using a pan-tilt mechanism but the scan time further increases by the factor of number of vertical scan lines. An ultrasonic sound sensor inspired from bats sends out an ultra sound which gets reflected back from the obstacle. Based on the time between the signal sent and received the distance at which the obstacle is can be determined. But if the sound reflects from more than one obstacle it might detect false features. Also a sonar projects out rays in a cone and hence information about more than a single point is obtained. Laser range finders use time of flight measurement of transmitted light pulse. Triangulation and high speed of light helps in getting range information at sub-millimeter accuracy. Hence Laser range finders are being used for reconstruction of archeological sites as well [10]. Also the refresh rates of the Laser range finders are very high. A 3D point cloud can be obtained by rotating it about an axis. Such an arrangement has been used in many indoor and outdoor robots. This paper shows a 2D Laser range finder being rotated about an axis to get a 3D scan of the surroundings. Also using the standard computer interfaces about 115000 points were achieved in 12 seconds [2]. The robot Kurt3D [11] uses similar such mechanism using AIS 3D ranging device to get range information in 3 dimensions for 6D SLAM. After getting the range information in 3D dimensions visualizing it in real time is also a major task. 3D range finding has also been widely used in autonomous cars which participated in Darpa Urban challenge. The autonomous car Stanley (junior) uses a rotating LIDAR (light detection and ranging). This custom built laser uses an array of vertical sensor which is rotated along an axis perpendicular to the road plane. This helps in giving a 360 degree field of view with one million point range information. Use of the Laser range finders on Snake robots is not possible due to their form factor (both their size and weight) as compared to the snake module’s size built around a standard RC servo. Ultrasonic range finders and Sharp IR have become popular and are used in micro robots because they are less expensive and small. EPFL lab’s amphibot [3] uses stereo vision to detect obstacles. Getting depth information from two images using pixel correspondence is a computationally intensive task. One more option is to use time of flight cameras like the Swiss range finder. It has been used in one rescue robot here [4] but again the size of these cameras is so large that it prevents their comfortable usage on Snake robots. This falls under passive optical non-contact scanners as described here [5]. Structured light scanners which fall under the category of active scanners use an energy source to illuminate the object and a camera to capture the illuminated object. By using digitally projected patterns one can get 3D information by triangulation. Some methods which use a sweeping a red laser line as used in the David Laser scanner.
require the projector and camera calibration. This helps in calculating the transformation matrix to construct the 3D point cloud from the illuminated object. One interesting technique which does not require calibration is the 3-phase scanning [7]. In this paper I present a low cost sensor which gives information about depth using structured infrared light and is miniature among the existing scanners discussed above. Also I present a robotic snake skin for tactile sensing using differential capacitance.

II. 3-PHASE SCANNING

This method involves illuminating the object with fringes which are sinusoid illuminated with traveling fringes the phase information of each and every pixel can be obtained. This pixel level phase information can be mapped to the depth. Traditional phase shifting algorithm requires the calculation of arc tangent which makes it computationally slow. Advancement to this technique is show in the paper on fast 3-phase scanning. Fast-3 phase shifting method is composed of phase wrapping and unwrapping. Phase wrapping is the processing of calculating the phases of each pixel and unwrapping is for removing the discontinuity that occurs at 360 deg. The phase unwrapping in the previous method was slower because it required calculation of fringe centers and normalization. But this was solved in fast 3-phase by using a look up table and simple intensity ratio calculation. But in most of the structured light projects the cost of the projector increases the total cost of the experimental setup. To overcome this I designed a new low cost fringe projector using an IR LED. I name it the “nano-projector” (fig.1) as compared to the micro pocket sized projectors. Initially it was thought to choose fringes formed using a laser pointer using diffraction grating but then it requires the fabrication of the grating which is expensive. Also the use of laser pointer in visible spectrum was avoided because it could cause damage to the observer when fringe pattern fall onto him while scanning.

III. NANO PROJECTOR

The arrangement (fig.1) shows the exploded view of the nano projector. It has an IR LED, a circular transparent film with the fringe pattern, hollow cylindrical tubing and a plano convex lens. The cost of micro-film development was more than the camera’s cost and hence low cost alternatives were looked into. The best among such was printing the fringes onto a transparent plastic sheet using a Laser printer. The problem was that the intensity of the fringes formed are to obey the equation below [8]:

\[ I(x, y) = I'(x, y) + I''(x, y) \cos[\Phi(x, y) - \alpha]. \]

When the resulting fringe pattern was magnified the fringe lines were in a zigzagged fashion (fig.2). This happened because the print head of the printer tried to approximate its position to print the image. To prevent this, lines which were of finite intensity (either 255 or 0) and that were in multiples of exact pixel thickness were drawn and printed. Now the print head’s position approximation did not occur. Lines of varying thickness were printed as shown in fig.3. More are the fringes in the film more will be the detail in the reconstructed 3D model. One more disadvantage of increasing the number of fringe lines with in the limited area of the projection transparency is that it comes at the cost of reduced line thickness. When projected the darker fringes did not form properly. Among all fringe patterns tried and tested, the fringes with 4 lines per mm were chosen.

3 such nano-projectors were constructed and were fitted to the CMOS web-camera (fig.7). Experiments were conducted with both visible light and IR light. The formation of fringes was proper with IR light than the visible light. The webcam was modified to capture IR light by removing the IR filter. This entire system of the nano-projectors along with the camera was constructed under 10 dollars. The angle between the

Figure 1. A)Exploded view of nano-projector B)parts of nano-projector

Figure 2. A)Proper Fringes B)Improper Zig-zagged fringes

Figure 3. Fringes with various spacing printed on transparent sheets
successive nano-projectors was arranged such that the fringes from each nano-projector were consecutively out of phase. The following (fig.4) are the consecutive frames caught using visible illumination and IR light. The coding was done OpenCV in C.

There are two reasons for which the fringe pattern using IR light was better. One, the Laser printer heats the sheet a bit so the density of the print material at the center of the printed pixel was more than at the corner. For visible light this was dark enough to be opaque and for IR it was translucent. Thus even the constructed 3D point cloud (fig.5) was better using IR light than the visible light. Generally the longer wavelength of light diffracts more than the shorter wavelength. The infrared light diffracted more than the shorter wavelengths in the visible light and thus the edges of the fringes formed by infrared light were more blurred than the visible light. This also resulted in a better 3D point cloud using IR light.

The 3D matrix of the points obtained as the output were visualized in processing, matlab, GNU plot and Google sketchup. It was observed that the 3D point cloud handling capabilities of Matlab and GNU plot were poor compared to Processing software. Processing was able to handle the 3D point cloud effortlessly and google sketchup was comparably good. The points for the above sample were 50,000. The depth for some of the features in the object was not pronounced because the nano-projectors were manually aligned. Better results were obtained using a single nano-projector mounted on a tilt servo with the camera as shown above. The servo had an analog potentiometer and minimum angular resolution of 0.09 was theoretically possible but practically achieved resolution was 0.63 degree. This way the fringes could be more precisely positioned.

The following is a variant of the 3D sensor. As miniature as the camera and LEDs can get so will the sensor. Here is another sensor constructed using a miniature camera. The weight of the sensor is 23 grams. Also by using more powerful IR LEDs higher projection distances can be achieved. The above LEDs used could project the pattern up to a distance of 2 meters at a maximum that could be detected by the webcam. Also the current consumption is not high. Each LED’s peak current is 15mA and the camera consumes not more than 500mA. Bigger laser range finder like the LMS-200 weighs 4500 gm and has a power consumption of 20W. I feel low cost 3D scanner implemented based on the above idea will help in reducing the cost which goes into buying the sensors and will save battery power.

Figure 4. A-C) Object (box) illuminated with visible light fringes D-E) Object illuminated with IR-light fringes

Figure 5. A) Point cloud from visible light fringes detecting edges B) Point cloud from IR light showing even the face of the box C) Side view of the point cloud showing the depth of the box (object)

Figure 6. Servo, IR camera and Nano-projector arrangement.
The nano projector scanner proposed here builds a 3D point cloud in under a second (both the mechanized as well as the non-mechanized). Using the non-mechanized version 3D point clouds were output at around 5-7 fps which is again constrained by the native frame rate of the web-camera.

Also one major limitation in structured light sensing is the cost of the projector involved. If high quality 3D reconstruction is required using digitally projected fringes then the projector needs to be of good quality. Handheld mini projectors have been launched about an year ago and their price has been slowly coming down but still are expensive. Also the use of a projector increases the cost of implementing a structured light scanner.

Some of the sensors for force measurement like Flex force sensors which are based on the principle of resistive foil strain gauges are very fragile. This limits their usage in designing a force sensitive snake skin. Also when they the surface of the sensor is punctured or torn the sensor stops functioning because the continuity of circuit in the resistive foil is lost. The sensor I presented here showed no change in performance even after it was torn and punctured. Also it was constructed under a dollar. Also this form of sensing helps in search and rescue scenario. This module on the Snake robot can help sense humans stuck in the debris with touch. It can also help differentiate between grass, leaves and ground by contact which is some of the environmental features that a natural snake encounters in the wild. It is also known that capacitive sensing can sense water (moisture) [9].
TABLE I. SNAKE SKIN SENSOR VALUES

<table>
<thead>
<tr>
<th>S.NO</th>
<th>TYPE OF SURFACE</th>
<th>MIN VAL</th>
<th>MAX VAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>HUMAN SKIN</td>
<td>110</td>
<td>4400</td>
</tr>
<tr>
<td>2.</td>
<td>PLANT LEAVES</td>
<td>27</td>
<td>75</td>
</tr>
<tr>
<td>3.</td>
<td>PRESSURE APPLICATION</td>
<td>0</td>
<td>13-16</td>
</tr>
<tr>
<td>4.</td>
<td>GENTLE TOUCH (FLOOR)</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>

V. APPLICATION TO SNAKE ROBOTS

I built several prototypes of snake robots (fig.10) in the past which were more design oriented. The first prototype was a planar snake showing horizontal undulation. Some were amphibious modules with wireless camera as the feedback for manual mode operation. The latest prototype is a 12 DOF snake robot for which a new modular head has been designed and constructed. It encompasses differential capacitive sensing as discussed in this paper. Also it has the 3D nano-projection sensor. The module weighs 53 grams including the sensor. Also it uses shock absorbing foam as a protection against impact. It has two sets of servos one for the horizontal and the other for the vertical. Each set of servo a controlled by a custom controller built around Atemga8. It can show 3D gait patterns.

VI. POSSIBLE IMMEDIATE APPLICATIONS OF THE SENSOR PRESENTED

A. Scanning rocks (exploration rovers)

Structured light scanning helps in constructive the 3D model at pixel level accuracy. In one scenario bones were collected from an excavation site by zoo-archaeologists and were reconstructed in 3D at a local site using structured light. But by using miniature sensors one can reconstruct the 3D model of skeletons, artifacts etc then and there on the site itself. This also limits the damage involving in transporting the artifacts to local or remote site. The miniature presented here can easily...
be carried around in pocket. One more scenario is that the sensor can be mounted in the end effector of robotic arm of an exploratory rover. Since it is miniature the complexity in end effector’s design is reduced.

Figure 11. Model of exploratory rover scanning rock using Nano-scanner

B. Camera Capsule

Given that today miniature cameras and miniature IR LEDs are easily available. One can use the following design for a camera capsule (12) and map the internals of the body (the intestines, esophagus etc in 3D). Also it can be integrated into design of nano or miniature medical robots for endoscopy.

Figure 12. Camera capsule with nano projectors

C. Mapping for Outdoor macro robots like autonomous cars.

Since the sensor is miniature and based on LED it can be easily combined into the car’s headlights without much modification of the cars basic design. One such design implementation is shown below. One can have a single sensor with tilt mechanism but it would be subject to a mechanical point of failure.

Figure 13. Scanner designed for outdoor robots (autonomous cars)

An attempt was made to construct one such sensor as shown below. The sensor was not able to project fringes properly because of two reasons.

a) The IR bulb chosen was designed for heating but not for focusing and projecting a collimated beam of light.

b) And there was no lens system for the above setup. The lack of resources high watt IR LED prevented me from implementing a long range sensor for outdoor robots. But the basic idea of 3 phase projection sensor remains the same. However it was observed that the object could be illuminated to a distance of 10 meters. The IR light sources available today can project IR light from tens to hundreds of meters. Also desktop projectors cannot project light at farther distances but the fringes formed using an IR projector can be seen by an IR camera even at distances greater than 10 meters.

VII. CONCLUSIONS AND FUTURE SCOPE

Conclusions and future scope:

1) This paper marks the invention of a whole new range of miniature 3D sensors with the new 3 phase nano projectors which are not only applicable to Snake robots but micro and macro robots in general which require the construction of 3D point cloud.

2) This also marks the invention first snake robot module with differential capacitance sensing which can distinguish between certain terrain features and the first Snake robot which over the limitation imposed on the usage of an Laser range finder.

3) The sensor is extremely low cost and should help the researchers with financial constraints in buying high end sensors.

The point cloud can be refined, texture mapped and surface rendering can be done. This can be applied in making possible the sub 10,000 USD autonomous car.
REFERENCES


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[8] Song Zhang, Piesen S. Huang, “High-resolution real-time three-dimensional shape measurement” Optical Engineering 45(12), 123601 (December 2006)


