Low cost 3D obstacle perception and tactile sensor for Micro and Macro robots (A Technical Report)

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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 are very costly. In this paper I present the design, construction and working prototype 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 also 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 industrial 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 then a sensor for 3D scanning and mapping is required. The sensory feedback can be about the immediate terrain 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 cameras, time of flight cameras etc are being used for quite a long time in both mobile and modular robots to get range information and thus help the robot in its perception about the immediate surroundings. An infrared range finder sends out a light pulse which gets bounced of the obstacle. Based on obstacle's 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 are used. A rotating IR is used on the head of the Snake to get the points in a 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 sensor. 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 a factor of the number of vertical scan lines. An ultrasonic sound sensor biologically inspired from a bat 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 obstacles. Sonar is better than an IR range finder because it projects out rays in a cone and hence range information about more than a single point is obtained. A Laser range finder uses time of flight measurement of transmitted light pulse. Triangulation and high speed of light helps in getting range information at sub-millimeter accuracy. Laser range finders are being used for reconstruction of archeological sites as well [10]. Also the refresh rate of the Laser range finders is 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. Paper[2] 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 range points were achieved in 12 seconds [2].The robot Kurt3D [11] uses a similar mechanism with the AIS 3D ranging device to get range information in 3 dimensions for performing 6D SLAM. After getting the range information in three dimensions, its visualization in real time is another major task. 3D range finding has also been widely used in autonomous cars like the ones 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 sensors, which is rotated along an axis perpendicular to the road plane. This helps in giving a 360 degree field of view with range information of one million points. However using 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 which is built around a standard RC servo. Ultrasonic range finders and Sharp IR have become popular and are being used in micro robots because they are less expensive and small. EPFL lab's amphi-bot [3] uses stereo vision to detect obstacles. But getting depth information from two images using pixel correspondence is a computationally intensive task. One more option is to use a time of flight camera 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 The Swiss range finder 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 use a sweeping red laser line like the one in the David Laser scanner [6] which requires 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 sinusoidal phase shifted [7]. From a series of images of the object 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 paper[8] 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 individual pixel and unwrapping is for removing the discontinuity that occurs at 360 deg. The phase unwrapping in 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. Also in most of the structured light projects the cost of the projector increases the total cost of 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 it requires the fabrication of grating plates which is expensive. Also the use of laser pointer in visible spectrum was avoided because it could cause damage to the observer's eyes while experimenting or while using the sensor.

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

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 should to obey the equation below [8]:

$I_1(x, y)=I'(x, y)+I''(x, y)\cos[\Phi(x, y)-\alpha]$. .

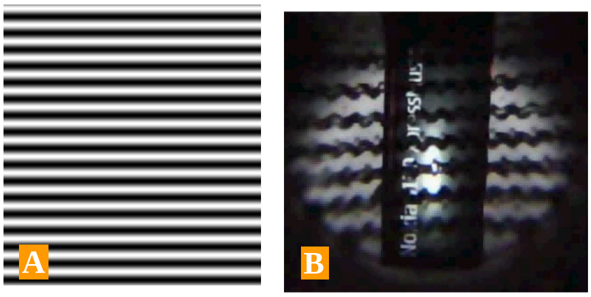


Figure 2. A)Proper Fringes B)Improper Zig-zagged fringes

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 film is that it comes at the cost of reduced line thickness; as a result the projected fringes did not form properly. Among all fringe patterns tried and tested, the fringes with 4 lines per mm were chosen.

Figure 3. Fringes with various spacing printed on transparent sheets

3 such nano-projectors were constructed and were fitted to a 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

successive nano-projectors was arranged such that the fringes from each nano-projector were consecutively out of phase. The following figure (*fig.4*) shows the consecutive frames caught using visible illumination and IR light. The coding was done in C and OpenCv was used for Image processing.

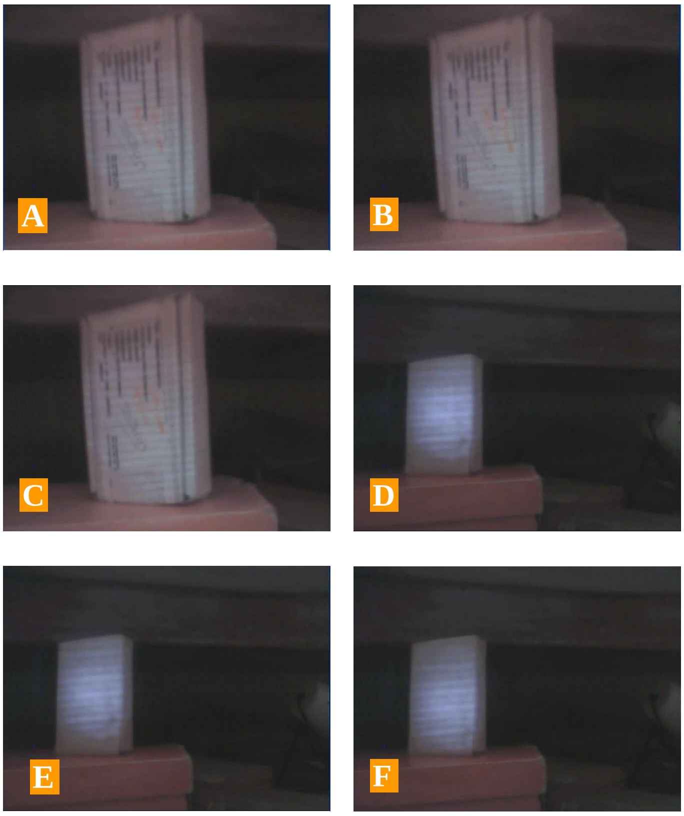


Figure 4. A-C)Object (box) illuminated with visible light fringes D-E)Object illuminated with IR-light fringes

There are two reasons for which the fringe patterns formed 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 the density 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. In general 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 thus resulted in a better 3D point cloud using IR light.

The 3D matrix of the points obtained as the output was visualized in processing, matlab, GNU plot and Google sketchup. It was observed that the point cloud plotting capabilities of Matlab and GNU plot were poor compared to Processing software [13]. 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 in *fig.6*. The servo had an analog potentiometer and a minimum angular resolution of 0.09 was theoretically possible but practically achieved resolution was 0.63 degree. This way the fringes were precisely positioned.

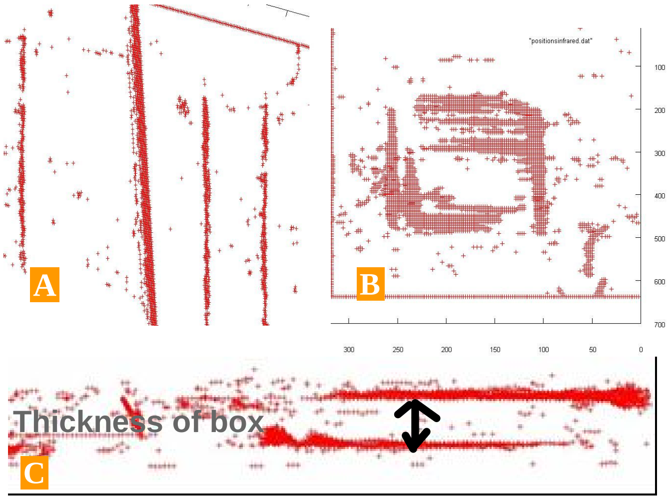


Figure 5. A)Point cloud from visible light fringes detecting edges B)Point cloud from IR light showin even the face of the box C) Side view of the point cloud showing the depth of the box (object)

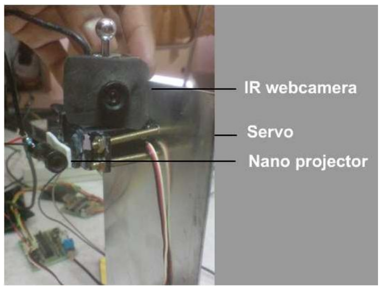


Figure 6. Servo,IR camera and Nano-projector arrangement.

Fig 7.a,b show a variant of the 3D sensor. As miniature as the camera and LEDs can get so will the sensor. Fig 7.c shows another sensor constructed using a miniature camera. The weight of the sensor (*fig 7.c*) is just 23 grams. Also by using more powerful IR LEDs higher projection distance can be achieved. The IR LEDs used here were able to project the pattern up to a maximum distance of 2 meters as detected by the web camera.. Also the current consumption of the sensor is very low compared to a Laser Range finder. Each LED's peak current is 15mA and the camera consumes not more than 500mA.Bigger laser range finders like the LMS-200 weigh 4500 gm and have a power consumption of 20W. I feel the low cost 3D scanner shown in this paper will help in reducing the cost which goes into buying the sensors and will also make a robot's power consumption lesser.

The nano projector based scanner proposed here builds a 3D point cloud in under a second (both the mechanized as well as the non-mechanized versions). Using the non-mechanized version 3D point clouds were output at around 5-7 fps which is again dependent on the native frame rate of the web-camera used.

Also one major limitation in structured light sensing is the cost of the projector involved. If high quality 3D reconstruction is required by 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 are still expensive. Also the use of a projector increases the cost of implementing a structured light scanner

Figure 7. A)Model of camera with Nano projectors.B)Constrcuted Scanner with webcam and nano-projectors C)Miniature scanner with Pinhole camera D)Sharp IR range sensor

IV. SKIN SENSOR FOR SNAKE ROBOT

Here I present a new sensory skin for Snake robots. The skin is based on the idea of differential capacitance. A microcontroller's pin has some capacitance and resistance. When a tin foil is attached to the pin and touched the variation of the capacitance observed is noticeable. But this is limited only to human touch or requires the presence of a conducting surface. Now two tin foils can be used and the differential capacitance between them can be varied by changing the separation distance between them.(9).Based on this idea a sensory skin was design as shown in *fig.8*. It has two tin foils, two insulating poly vinyl sheets and shock absorbing foam *fig.8*. Also non-conductive springs embedded in the shock absorbing foam were used. This helps in the compression and decompression of the arranged layers. When the face of the Snakes module is in contact with a surface or pressure is applied on it, the springs and the foam compress .Thus the capacitance value changes. And by measuring the capacitance of the single plate relative to the ground when touched, I was able to differentiate between a plant leaf and human skin. The force applied could be distinguished from the above nature of touches. The following are the graphs (*fig 9, table 1*).The capacitance was measured in terms of time (by incrementing a counter variable) taken to discharge the charge on a micro-controllers pin onto another pin set as input. The response from the sensor was almost instantaneous.

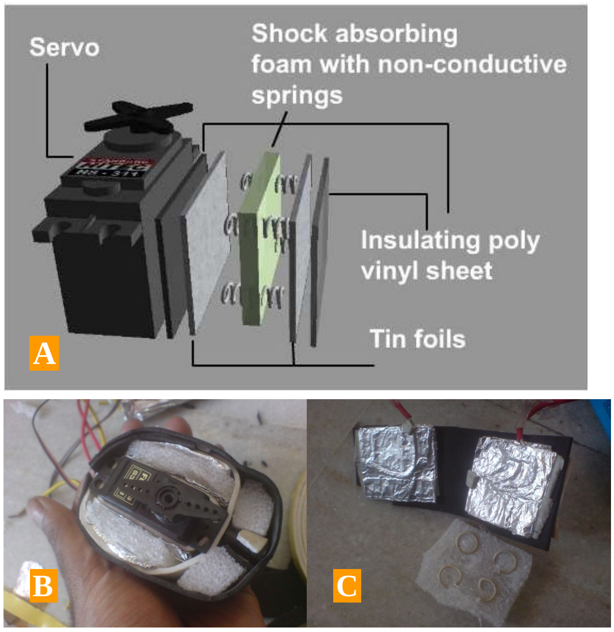
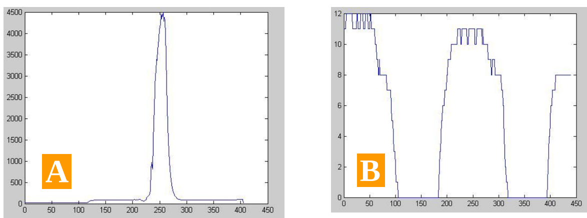


Figure 8. A)Exploded view of the capacitance skin sensor B)Constructed Snake module C)Tin foils with foam and non-conducting springs.

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 for rugged terrain. Also when 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. This form of sensing helps in search and rescue scenario in another way as well. This module (*fig-8.b*) on the Snake robot can help sense humans stuck in the debris with touch. It can also help differentiate between grass, leaves and ground with contact which are 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].



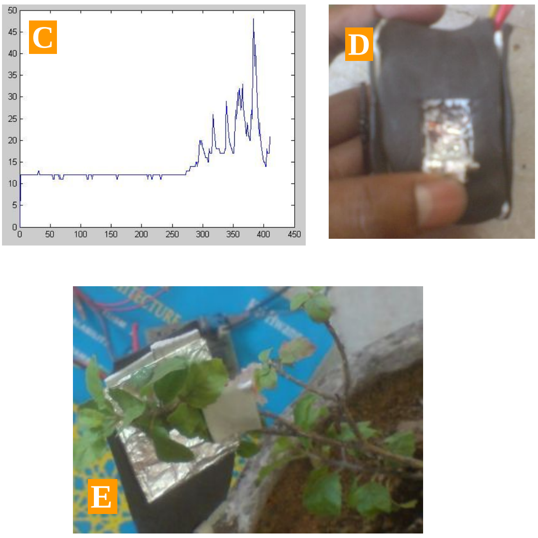


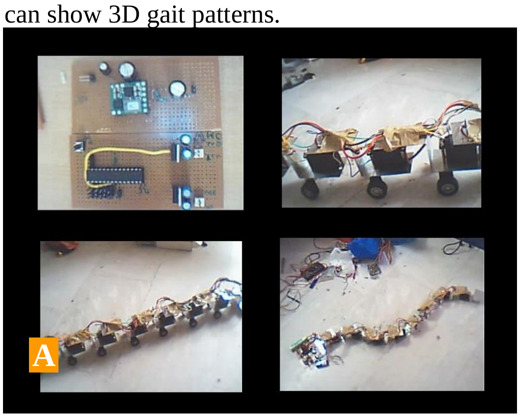
Figure 9. Sensor response for A) human skin B)for pressure C) For plant leaves D) Sensor torn and punctured E)Sensor touching plant leaves

TABLE I. SNAKE SKIN SENSOR VALUES

S.NO	SENSOR READINGS		
	TYPE OF SURFACE	***MIN VAL***	***MAX VAL***
1.	HUMAN SKIN	110	4400
2.	PLANT LEAVES	27	75
3.	PRESSURE APPLICATION	0	13-16
4.	GENTLE TOUCH (FLOOR)	20	23

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 in which a wireless camera was used for feedback and had manual mode of operation. The latest prototype is a 12 DOF snake robot for which a new modular head has been designed and constructed. It uses differential capacitive sensing as discussed in this paper. Also it has the 3D nano-projection sensor. The module weighs 53 grams including the sensor and it uses shock absorbing foam for protection against impact. It has two sets of servos one for horizontal and the other for vertical motion. Each set of servos is controlled by a custom controller built around Atemga8.It can show 3D gait patterns.



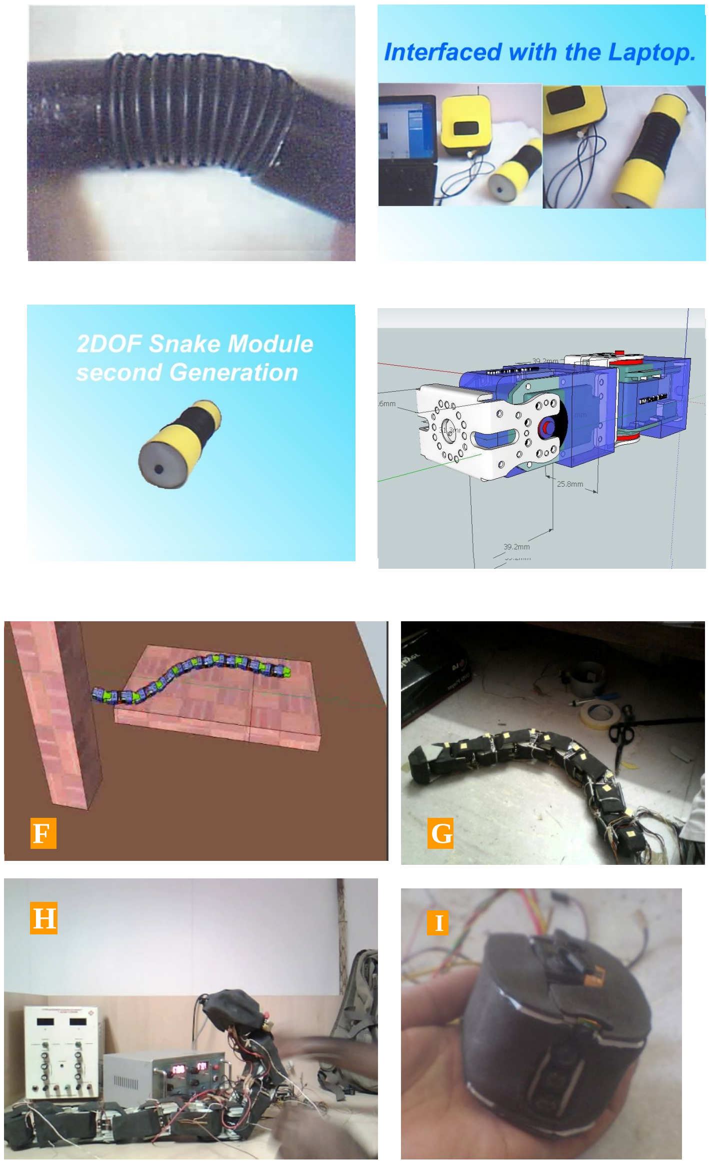


Figure 10. A)Snake with 1DOF modules B -D)Amphibious Snake modules E-H)12D0F Snake with shock absorbing foram I)Snake head module with 3 phase nano-scanner and capacitance skin

VI. POSSIBLE IMMEDIATE APPLICATIONS OF THE SENSOR PRESENTED

A. Scanning rocks (exploration rovers)

Structured light scanning helps in constructing the 3D model at pixel level accuracy. In one scenario bones were collected from an excavation site by zoo-archeologists and were reconstructed in 3D at the 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 involved in transporting the artifacts to a local or remote site. The miniature sensor presented here can be easily carried around in pocket. One more scenario is that the sensor can be mounted on the end effecter of a robotic arm on an exploratory rover. Since it is miniature the complexity in the end effector's sensory design is reduced.

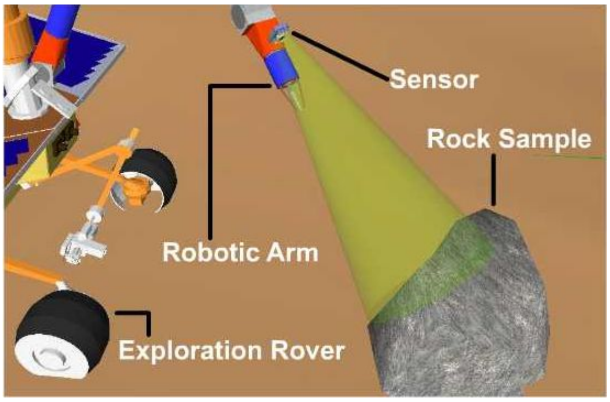


Figure 11. Model of exploratory rover scanning rock using Nano-scanner

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 (*fig.12*) and map the internals of the body (the intestines, esophagus etc in 3D).Also it can be integrated into the design of nano or miniature medical robots for endoscopy.

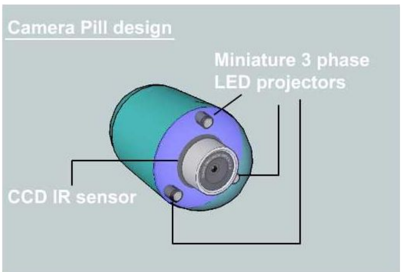
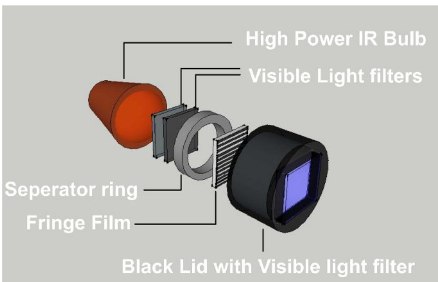


Figure 12. Camera capsule with nano projectors

C. *Mapping for Outdoor macro robots like autonomous cars.*

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



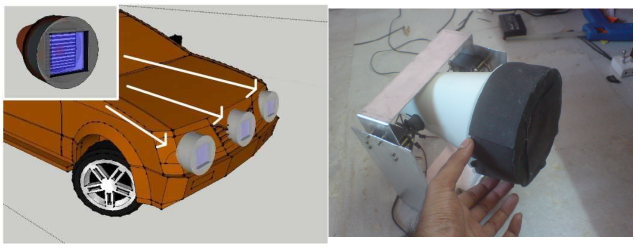


Figure 13. Scanner designed for outdoor robots (autonmous cars)

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 a 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 several 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 using the new 3 phase nano projector which can be used only on Snake robots but micro and macro robots in general.
2) This also marks the invention of the first snake robot module with differential capacitance sensing which can distinguish between certain terrain features and the first Snake robot which overcomes the limitation imposed by a Laser range finder.
3) The sensor is extremely low cost and should help the researchers with financial constraints involved in buying high end sensors.

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

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