Design and Development of a Vertical Scanning System for 3D Images Acquisition

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Abstract: - This paper presents the work that was developed to propose an alternative solution to upgrade the perception system of a Pioneer 3-AT mobile robot. The goal was complement the range measurement system based in ultrasonic sensors. For this, the idea was design and builds a mechanical system capable to tilt automatically a laser range finder LMS200, in order to be able to acquire 3D images of the robot environment. 3D images can be used to determine the distances to probable obstacles, and if it's necessary, robot could identify a set of patterns and in consequence could find different objects.

In the next pages we will explain all the stages from the development of the device, the documentation used and the theory implemented to obtain goods results.

Key-Words: - 3Dimage, Scanning, Telemeter, Microcontroller, Mechanics, Mechatronic, LMS200, PIC16F870.

1 Introduction

The project here described is focused to develop a low cost navigation system profiting from the existence of commercial devices, making minimal necessary changes.

Behind the navigation of mobile robots there are a lot of techniques, using different sensors, for example, but to obtain good results it's necessary use two or more sensors concurrently.

For example, when an ultrasonic sensor is used the robot can know only the distance to the objet, if there is one. Same situation appears when it uses a light sensor, IR sensor, or point laser sensor, but it can't identify the object.

Other device widely used is the video camera, but with this one, colors (or intensity) and some other parameters can only be detected, but determining the distance to the objects requires a lot of processing; this is the main argument to wish use a laser range finder to obtain distances to the objects.

The advantage that we have to use a modified 2D range finder to generate 3D images is that it takes the distances and with them robot can find and identify obstacles.

This paper presents the principal problems and solutions proposed to create all the components that in group allowed build a 3D scanner using the Sick LMS200 (Fig.1) that we have in our laboratory at the Technological Institute of Toluca.

Fig.1. Telemeter laser range finder LMS200

To make an easier study and development of the system here described, the construction of the tilting system (TS) can be divided in three principal parts: mechanical, electronic, and programming part.

2 Mechanical Part

2.1 Determining structure's center of mass and moment of inertia

The first activity was to determine the center of mass from the LMS200, and the box (*turret*) where the telemeter would be mounted (Fig.2) to find the best place to put the pivot axis that would transmit the motion to the telemeter, creating in this way a new degree of freedom around "X" axis.

The pivot must be placed on line with the coordinates that represent the position of the center of mass, it is very important in the design because it is the point where the motor will receive less stress.

In this activity the theory about center of mass and moment of inertia was used, to determine approximately the real position of these

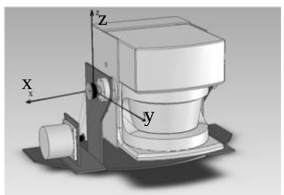

Fig.2. Design of the TS with the LMS200 mounted in the turret.

characteristics.

Center of Gravity: The center of gravity is the point where the resultant weight of a particles system is concentrated [1], [4].

$$\bar{x} = \frac{\sum(\tilde{x} \cdot W)}{\sum W} \qquad \bar{y} = \frac{\sum(\tilde{y} \cdot W)}{\sum W} \qquad \bar{z} = \frac{\sum(\tilde{z} \cdot W)}{\sum W} \quad (1)$$

Where:

$\bar{x}, \bar{y}, \bar{z}$ represents the coordinates of the center of gravity of a particles system.

$\tilde{x}, \tilde{y}, \tilde{z}$ represents the coordinates of each particle present in the system (centroid).

$\sum W$ is the sum of all the weights of all the particles in the system.

Center of Mass: The center of mass is the point where the mass from a particles system with a constant acceleration, for example the gravity, is concentrate at that point [1].

$$\bar{x} = \frac{\sum(\tilde{x} \cdot m)}{\sum m} \qquad \bar{y} = \frac{\sum(\tilde{y} \cdot m)}{\sum m} \qquad \bar{z} = \frac{\sum(\tilde{z} \cdot m)}{\sum m} \quad (2)$$

Where:

$\sum m$ is the sum of all the masses of all the particles in the system.

m is the mass.

The difference on these two terms that sometimes are interpreted as the same is that the second one is independent from the gravity force [1].

Another form to explain the relationship and difference of these terms is that the *center of mass of a particles system* is used when in the calculations the handling of the properties is related to the mass of the particles, and is used the *center of gravity* when the properties are associated with the weight of the particles [3].

Into the project it was necessary determining the center of mass because the properties that we knew were the mass and the density. The telemeter has a mass of 4.5 Kg and the turret was designed and made in aluminum that has a density of 2,700 Kg/m3.

The first step to determine the center of mass was to divide the telemeter and the turret in different regular figures to find the main characteristics of individual forms and then combine them into a composite figure (Fig.3).

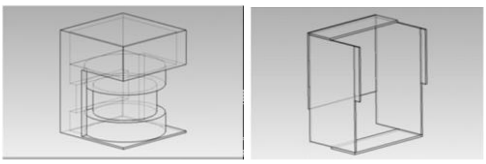

Fig.3. Representation of the turret and telemeter LMS200 by regular geometric figures.

The second part of the project was to define a coordinate system to determine the exactly position and dimension from every figure inside a space (Fig.4).

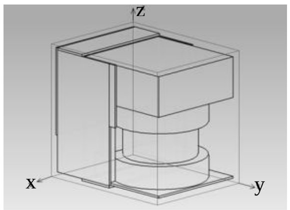

Fig.4. Representation of the turret and telemeter inside of a coordinate system of reference to help calculate the position of the center of mass.

Equations (8) to (10) and (13) to (15) were used to calculate the center of mass of each part, with this result also was determined the position where the pivot was placed in the turret by means of equation (2), with the purpose of decreasing the moment of inertia in the general system. The results are shown in Table I.

TABLE I

Position of the centroid of each regular figure that represent the turret and the LMS200, and the center of mass of the TS.

DESCRIPTION	COORDINATES INTO THE AXIS (mm)			MASS OF THE ELEMENTS (g)
	X	Y	Z	
Centroid of 1A	160.6	57.2	96.2	173.56032
Centroid of 1.1A	160.6	117.2	141.5	9.891072
Centroid of 2A	1.6	57.2	96.2	173.56032
Centroid of 2.1A	1.6	117.2	141.5	9.891072
Centroid of 3A	81.1	1.6	125.8	186.387264
Centroid of 4A	81.1	28.7	190.8	71.471808
Centroid of 5A	81.1	82.7	1.6	79.880256
Center of mass of the turret	**81.1**	**44.17749811**	**104.1724939**	**704.642112**
Centroid of 1B	81.1	132.2	95.7	17364.5198
Centroid of 2B	81.1	132.2	155.7	3960.33562
Centroid of 3B	81.1	158.45	66.2	7472.88067
Centroid of 4B	81.1	85.95	23.7	728.472914
Centroid of 5B	81.1	85.95	108.7	728.472914
Centroid of 6B	81.1	93.7	66.2	474.357705
Centroid of 7B	81.1	136.2	23.7	174.039348
Centroid of 8B	81.1	136.2	108.7	174.039348
Centroid of 9B	81.1	135.7	66.2	151.921303
Center of mass of the LMS200	**81.1**	**108.0683195**	**101.2673993**	**4500**
Center of mass of the TS	**81.1**	**99.41831777**	**101.660712**	**5204.64211**

At this point it is important to define that this method isn't exact when the real distribution of mass is unknown, e.g. in the telemeter, but it can be approximated.

By the previous reason, it was necessary to make use of a complementary method to determine the center of mass, this was the experimental method where two or more points must be selected on the extremities of a object to use each of them as pivot to put in equilibrium the system and then trace a perpendicular line at the horizontal to determine the center of mass on the point where the lines intersect.

After obtaining the center of mass and confirming the result, the next step was to determine the moment of inertia to know what type of motor is necessary to give movement to the mechanism.

The *moment of inertia* is a measure that gives the distribution reason of the mass in a particles system around one of its points [4]. In other words, it represents the inertia to rotate that a body has, knowing that it is the resistance to the acceleration, in this case angular acceleration [2].

There are two ways to calculate the moment of inertia, doing the corresponding integrals (3) in all the volume of the body, or using the defined equations

(4) to (7), (11), and (12), to be used in the regular bodies.

$$I = \int_m r^2 dm \qquad I = \int_V r^2 \cdot \rho dV \tag{3}$$

$$I_x = \sum (I_{\tilde{x}} + D_I \cdot m) \tag{4}$$

Where:

I is the moment of inertia

r is the perpendicular distance between the spin axis and an arbitrary element *dm*. “the moment arm”.

ρ density

V volume

I_x is the moment of inertia into a composite figure, respect the spin axis “ $\overline{X}$ ” that crosses the center of mass.

$I_{\tilde{x}}$ is the moment of inertia of each figure that composes the composite figure with respect to their spin axis *“ $\tilde{X}$ ”*, which crosses their centroid.

D_I is the distance between the axis “ $\overline{X}$ ” and “ $\tilde{X}$ ”, in each regular figure that form the composite figure.

As well as there are equations to calculate the area and volume also are defined equations to calculate the moment of inertia and the centroid in the regular geometric figures, as follow.

Prism:

$$I_{\tilde{x}} = \frac{1}{12} m(b^2 + c^2) \tag{5}$$

$$I_{\tilde{y}} = \frac{1}{12} m(c^2 + a^2) \tag{6}$$

$$I_{\tilde{z}} = \frac{1}{12} m(a^2 + b^2) \tag{7}$$

$$\tilde{x} = \frac{a}{2} + \Delta x \tag{8}$$

$$\tilde{y} = \frac{b}{2} + \Delta y \tag{9}$$

$$\tilde{z} = \frac{c}{2} + \Delta z \tag{10}$$

Cylinder:

$$I_{\tilde{x}} = I_{\tilde{y}} = \frac{1}{12} m(3 \cdot r^2 + L^2) \tag{11}$$

$$I_{\tilde{z}} = \frac{1}{2} m \cdot r^2 \tag{12}$$

$$\tilde{x} = C_x \tag{13}$$

$$\tilde{y} = C_y \tag{14}$$

$$\tilde{z} = \frac{L}{2} + \Delta z \tag{15}$$

Where:

$I_{\tilde{x}}, I_{\tilde{y}}, I_{\tilde{z}}$ are the moment of inertia around the axis indicated on the subscript.

a, b, c are the width (on axis X), length (on axis Y) and high (on axis Z) respectively in a prism.

$\Delta x, \Delta y, \Delta z$ are the displacement that the figure has respect the center of the coordinate system.

r, L are the radius and length respectively in a cylinder.

C_x, C_y are the coordinates center of the circular face on a cylinder.

For practical cases the use of regular figures that form a composite figure is most usual and fast [1].

The following stage of the project was find the moment of inertia of the turret and the telemeter, it was calculated with the aid of the regular figures that compose the system and the equations (5) and (11) corresponding with each figure defined in the device, to obtain later the moment of inertia of the whole system using equation (4), getting the results shown in Table II.

TABLE II

Moment of inertial (I) of each regular figure that represent the turret and the LMS200, and the moment of inertial of the TS.

ELEMENT	Moment of inertial (g·mm^2)	Moment of inertial (kg·m^2)	D_I(mm)
1A	669075.0336	0.000669075	111.9208649
1.1A	7620.378601	7.62038E-06	183.7337476
2A	669075.0336	0.000669075	111.9208649
2.1A	7620.378601	7.62038E-06	183.7337476
3A	274909.4099	0.000274909	125.8101745
4A	15552.50366	1.55525E-05	192.9464433
5A	21695.7438	2.16957E-05	82.71547618
1B	84740303.81	0.084740304	163.2033394
2B	6899234.681	0.006899235	204.2531028
3B	15638403.98	0.015638404	171.7231566
4B	178915.9829	0.000178916	89.15768335
5B	178915.9829	0.000178916	138.5752233
6B	125546.6727	0.000125547	114.7263265
7B	237099.6056	0.0002371	138.2466274
8B	237099.6056	0.0002371	174.2588018
9B	148639.1701	0.000148639	150.9865226
TS	**64692782.91**	**0.064692783**	

It’s important once again notate that the use of this method isn’t exact when the real mass or density distribution is unknown, as in the case of the telemeter, but it will be approximated to the real value if the center of mass is correctly calculated.

Knowing that the concept of *moment of inertia* in a rotational movement and the *inertial mass* in a linear movement are analogous [2], and making use of the second law of Newton, it is easy to calculate by means of equation (16) the required torque to move the telemeter and the turret, knowing that the moment of inertia of the system is 0.064692783 Kg·m^2 and that the required max angular acceleration is 2.61799 rad/s^2, the reason of this value is explained in *section 2.2*.

$$\tau = I \cdot \alpha \tag{16}$$

$$k = \sqrt{I/m} \tag{17}$$

Where:

τ is the torque generated by an angular acceleration and a moment of inertia, doing analogy to the second law of Newton in a rotational movement.

α is the angular acceleration of a body.

k is the radius of spin

2.2 Motor and power transmission system

The selected power transmission system is a mechanism of toothed pulleys and its respective synchronous belts type PowerGrip Timing moved by a stepper motor.

The driving pulley of the mechanism has 16 teeth with a step of 0.080 inches and the drove pulley has 40 teeth with the same step, with these data we can define the relation of movement in a scale of 1:2.5.

The selected motor is a stepper motor because the handling of the position is easy and the precision only depends of the step angle of the motor. The principal characteristics of the elected motor are: 3.5V/phase, 1.4A/Phase and 1.8deg/step.

In order to assure that the motor could be able to support the load, it was put under a torsion test using a mass of 2 Kg. placed at a distance of 1cm from the motor's shaft and using a work frequency of 208 Hz to produce a speed rotation around 62.4 RPM, because this is the needed to generate around 25 RPM (150°/s) of speed rotation on the telemeter LMS200 as in the 3-D Sweeping Laser Range-Finder commercial model.

The result of the test was satisfactory obtaining a torque of 0.1962 N·m (27.78oz·in) in the motor and in the driving pulley a torque of 0.4983 N·m (70.55 oz·in) that is more than the torque necessary to move the telemeter, which was calculated using (16) obtaining 0.1694 N·m (23.98 oz·in).

3 Electronic Part

The second part of the development of the TS had as objective to design the circuit (Fig.5) to control the mechanism, where to get the best results, it was divided in three general parts: control system, communication and power circuit, all of them have a specific job into the design as described below.

4.1 Control System

This element is formed by two encapsulated circuits, the microcontroller PIC16F870 (Fig.5) who has the job to identify and generate the different signals to produce the correct performing of the motor. Microcontroller lets modify and control direction, step clock, half/full step selection, and enable/disable phase power. It also communicates with the computer to receive commands and controls the whole mechanism.

The microcontroller works with a crystal oscillator of a frequency of 4 MHz, obtaining 1μs machine cycle time (T_{CM}).

The other integrated circuit is the L297 who is a stepper motor controller which is commanded by the signals coming from the PIC16F870. It produces the signals sequence needed to drive the stepper motor [8], [11], these signals are shown in table III if it's working at full step or in Table IV when working at half step.

4.2 Communication

This part of the circuit is very necessary because through it the user will be able to configure and to know the state of the system by means of a computer with serial port.

In this application we use a standard MAX232 to transform the TTL signals (0-5V) from the microcontroller to RS-232 signals (±12V) used by the COM port of the computer and vice versa.

The communication was configured to 9600

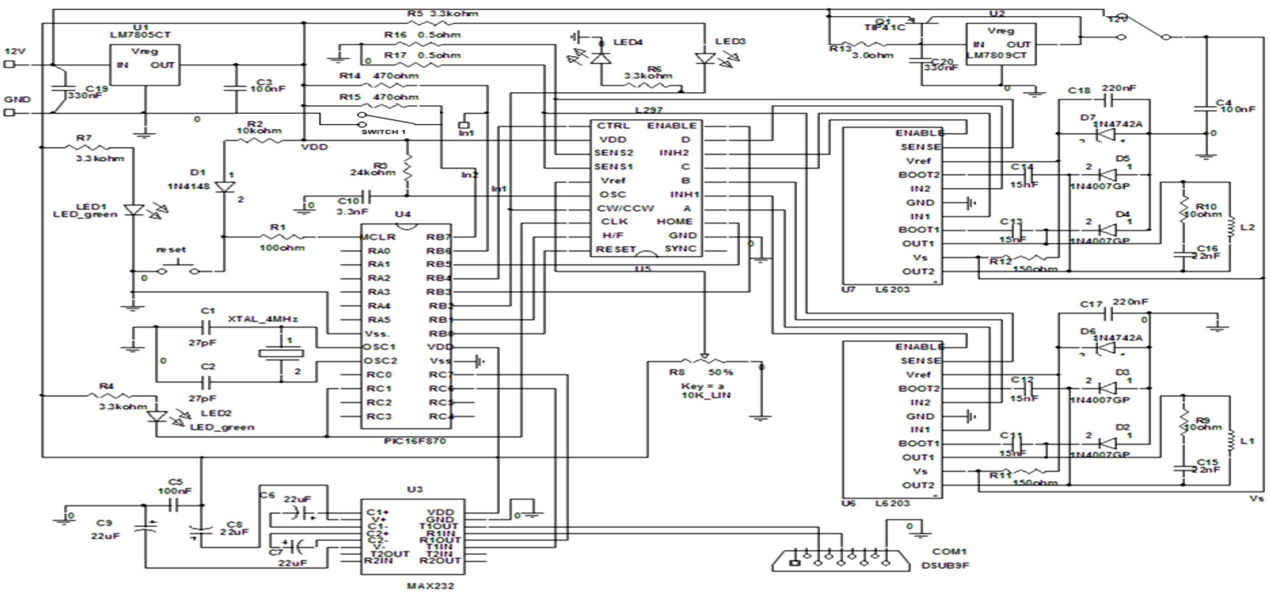

Fig.5. Designed electronic diagram for TS, to control a stepper motor with a computer using a PIC16F870.

bauds, 8 data bits and 1 stop bit being the standard values.

TABLE III

Required signals to move the stepper motor at full step

STEEP	CABLE A	CABLE B	CABLE C	CABLE D
1ST TIME	+ Vcc	GND	+ Vcc	GND
2TH TIME	+ Vcc	GND	GND	+ Vcc
3TH TIME	GND	+ Vcc	GND	+ Vcc
4TH TIME	GND	+ Vcc	+ Vcc	GND

TABLE IV

Required signals to move the stepper motor at half step

STEEP	CABLE A	CABLE B	CABLE C	CABLE D
1ST TIME	+ Vcc	GND	+ Vcc	GND
2TH TIME	+ Vcc	GND	GND	GND
3TH TIME	+ Vcc	GND	GND	+ Vcc
4TH TIME	GND	GND	GND	+ Vcc
5TH TIME	GND	+ Vcc	GND	+ Vcc
6TH TIME	GND	+ Vcc	GND	GND
7TH TIME	GND	+ Vcc	+ Vcc	GND
8TH TIME	GND	GND	+ Vcc	GND

4.3 Power Circuit

In the power circuit the correct election of a motor's drive was more exhaustive, because if in the design is used a circuit with low characteristics, it may cause damage or bad work of the motor and the full-bridge driver.

Determining what of the commercial drivers has the characteristics indicated to the job, it was necessary to use equations (18) to (20) with the characteristics of the motor as the current needed to obtain the appropriated torque to move the telemeter and the turret, and the desired max rotation speed.

$$power(W) = \frac{2\pi * [torque(N \cdot m)] * [rotation\ speed(rpm)]}{60} \quad (18)$$

$$power(W) = [voltage(V)] * [current(A)] \quad (19)$$

$$current(A) = \frac{power(W)}{voltage(V)} \quad (20)$$

With the results obtained, we chose the L6203, which has appropriated ratings of voltage and current to work, high switching speeds, protection systems, thermal shutdown and limit current sensor.

The configuration of the L6203 to do it works at a supply voltage range between 9V-12V was made using the datasheet documentation [10] and also calculating the correct values of capacitance and resistance needed to supply the appropriated power to the stepper motor, by using (21), (22).

$$R \cong V_S / I_p \quad (21)$$

$$C = I_p / (dV/dt) \quad (22)$$

Where:

- R is the value of the resistances *R9* and *R10* (Fig.5)
- C is the value of the capacitances *C15* and *C16* (Fig.5)
- V_S is the maximum supply voltage foreseen on the application.
- I_p is the peak of the load current.
- dV/dt is the limit rise of the output voltage (200V/μs is generally used).

4 Programming part

4.1 Microcontroller functions

In order to make that the system works, the microcontroller needs to be programmed appropriately. Into the program the main characteristics of control were configured, e.g. the input and the output pins.

We are using RB0-RB4 pins as digital outputs and RB5- RB6 as digital inputs in port B of the PIC16F870. Besides RC1 is a digital output in port C, port that also was configured to permit the communication via RS232 where RC7 is RX and the RC6 is TX. Detailed use of each pin is showed in Table V.

TABLE V

Function assigned at the pins of the PIC16F87670

No. Pin	Name of Pin	Function designed
12	RC1/T1OSCI	Pulse to the clock in on L297 that produce the next step.
17	RC6/TX/CK	Transmission of serial data.
18	RC7/RX/DT	Reception of serial data.
21	RB0/INT	At low state reset the stepper motor controller.
22	RB1	On low state full step work is selected, on high state half step work is selected.
23	RB2	Change the direction CW/CCW
24	RB3/PGM	Enable/disable the power on the motor
25	RB4	Define where the inhibit control currents will act
26	RB5	Input to detect when the stepper motor controller is in home (outputs to motor in 0101).
27	RB6/PGC	Input to detect when the telemeter is on the horizontal.

The microcontroller was programmed to communicate with a host computer via RS232 serial port, whereby the microcontroller receives characters strings that are commands or sends characters strings to indicate the state of the system and the actual position respect the horizontal.

A high level program (written in Java) is used to control the mechanism and acquire range data to compose 3D images.

The system has a default configuration, where the stepper motor moves at half steps and may give 180 range data lines in a whole frame of 64.8°. This configuration may be changed by the user to get more or less data lines to up and down respect the horizontal (maximum 126 range data lines per half frame), and the angular resolution may also be modified at 0.72° or 0.36° between the data lines.

The system recognizes 10 commands in ASCII code as shown:

1. (**r**) = homing of the mechanism.
2. (**n**) = in the settings means to leave the default values.
3. (**y**) = in the settings means to change the value of the settings as scan's limits and motor's step. In principal operation permits a continuous scan changing automatically the motor's direction on the limits.

4. (**f**) = changes at full step the resolution of the motor.
5. (**h**) = changes at half step the resolution of the motor.
6. (**+**) = in the settings permits increase the value of the upper limit or lower limit.
7. (**-**) **=** in the settings permits decrease the value of the upper limit or lower limit.
8. (**space bar**) = acceptation of the assigned limit values.
9. (**2**) = in principal operation, moves the telemeter upwards
10. (**8**) = in principal operation, moves the telemeter downwards.

5 Conclusions and Results

After making the necessary settings in all the system with different conditions of work, we obtained the first 3D image (Fig.6) with a resolution of 0.36° and 64.8° frame field of view of (180 range data lines), using the software designed by another lab student.

The maximum speed obtained in the scan of a whole frame was around 4.8 minutes, this speed could be enhanced making an exactly coordination of the system between the telemeter, microcontroller and host computer, processing the data image with an efficient method, but even so the max speed only could be not less than 7s per frame scan with 252 range data lines, because the telemeter and the microcontroller need at least 13ms to scan a line and 0.5ms to move the telemeter to the next position, respectively. Besides, the necessary time to let the computer process input data coming from the TS and the LMS200 must be equal to the time required by them.

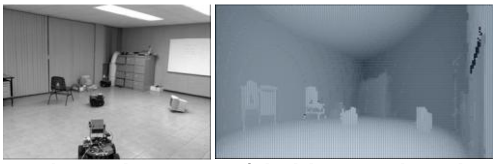

Fig.6. Photo and 3D image of the laboratory obtained with the developed system (Courtesy of F. Bucio, Tech. Institute of Toluca).

Home position is detected by means of the use of a microswitch; this method could be improved using an optical sensor or an inclinometer.

The present position of the mechanism is determined by means of the number of steps realized from the home position; to improve this information an absolute optical sensor could be used.

The TS can move up to 150 degrees/seg but the transmission of data from the LMS200 limits this operation, thus, at a speed of transmission of 9,600 bauds, working frequency by default of the LMS200. Working in this way, an image is obtained every 4,8 minutes. The LMS200 allows maximum speed transference 38,600 bauds, which would reduce transference time to a quarter of the current time. Additionally, the change to a strategy of type pipeline would allow improving this performance still more.

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