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A High Speed 3D Radar Scanner for Automation

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Abstract

A high speed three dimensional radar scanner capable of providing the high resolution range maps necessary for outdoor mobile robotic vehicles is described in this paper. Unlike traditional laser rangefinder based scanners, this sensor is intended to operate in real world environments plagued with dust, fog, and rain. The 94GHz pulsed time-of-flight radar system has a peak repetition rate of 250kHz, a 23cm beam focused at 8m with an effective 1° divergence, and a 180°x360° scanned field of view. DSP processing of the range data provides a reduced data rate while taking full advantage of the higher firing rate to improve accuracy and sensitivity to specular and poorly reflective targets

1 Introduction

Sensing capabilities are a key technology for the success of robotic automation. Data about a robot's surroundings is used to navigate, avoid obstacles, and perform task specific functions. Sensors acquiring such data need large fields of view to encompass the entire workspace, high scan rates to provide fresh, timely data, and the ability to function while mounted on moving equipment. Objects typically found in a target environment could include humans and similarly sized obstacles, vehicles of varying sizes, and a wide assortment of natural materials including rocks and dirt.

Laser rangefinder based scanners have proven capable of creating very high resolution range maps of the environment surrounding an autonomous vehicle.[1] However, such optically based systems have found most utility on indoor robots. When subjected to the dust, fog, and rain of an outdoor application, performance of a traditional laser rangefinding sensor degrades to provide limited utility.

A high resolution radar based scanner could prove to be more appropriate in real world environments. Radar, with its larger wavelength, has been shown to be unaffected by all of the environmental challenges to laser but comes with its own drawbacks. Typical radar systems have large beamwidths and slow scan rates, accompanied by concerns of significant antenna sidelobes, poor returns from specular targets, and poor range accuracy.

Previous work utilizing frequency modulated continuous wave (FMCW) radar techniques has shown that it is difficult to resolve multiple targets in a cluttered operating environment.[2] Additionally, FMCW requires the sensor to be aimed at a region of interest for a time equivalent to the duration of its frequency ramp in order to reliably resolve a target. This dwell time, which can decrease the effective scanning rate of the system, is proportional in duration to the desired downrange resolution of the sensor. Higher resolution sensing requires a longer ramp. Generating a linear ramp can be difficult over wide frequency sweeps. The combination of these challenges can make high speed scanning of accurate FMCW radar sensors difficult.

A pulsed time-of-flight (TOF) technique provides the ability to easily discriminate the first target from the multipath and multi-target returns, but requires a high precision timing mechanism to determine the range to target. Previous work has implemented a range gate based timing system in which the radar is pulsed once for each potential range bin, or range of interest.[3][4] Such a method greatly reduces the net data rate because the sensor must be aimed at the same target for a long period of time to complete the hundreds of samplings needed to fill the bins.

In most navigation and collision avoidance applications, a system needs only to know the location of the nearest target, and can therefore perform time of flight to the first return. In comparison to the previous work, the point sensor described in this paper uses a more complex timing method to provide a first target range reading for each pulse of the radar. Such a system allows higher data gathering rates, yields higher density range maps, and is not affected by the beam motion when scanning between sequential firings of the sensor.

The point sensor is mounted in a high speed mechanical scanner which directs the beam in a 180°x360° scan pattern.

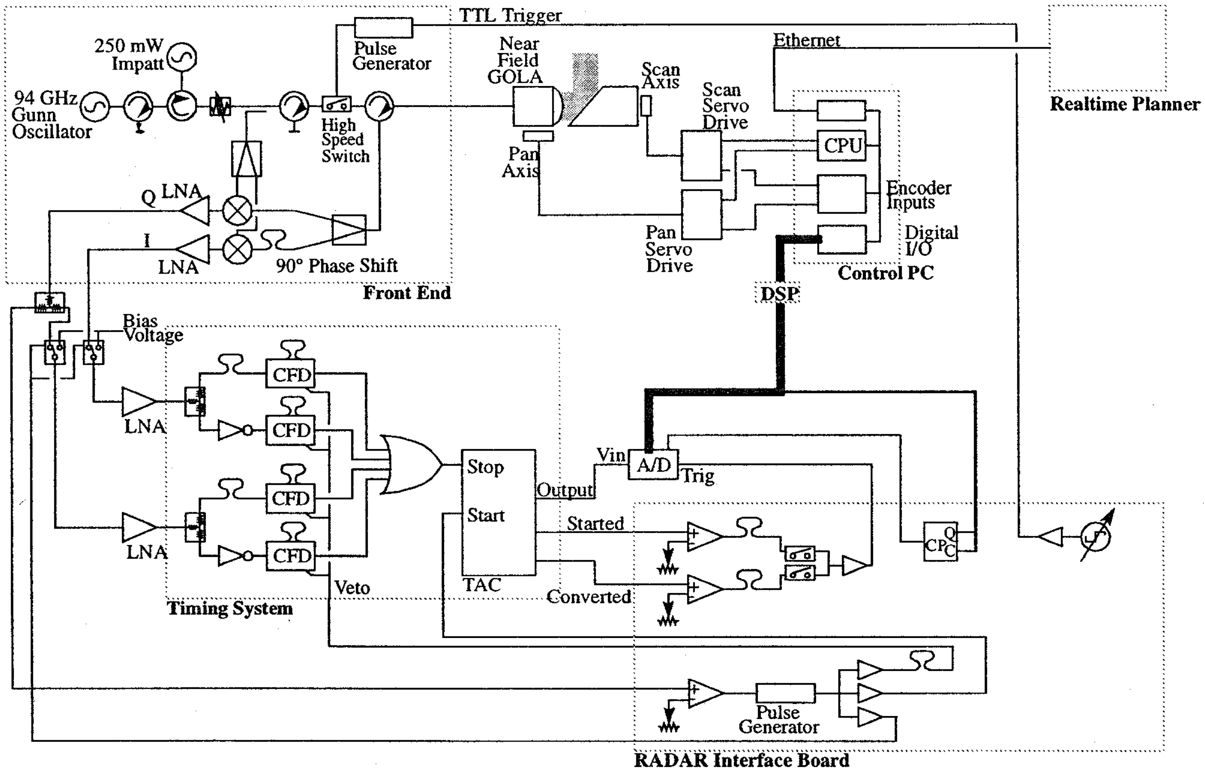

Figure 2: System block diagram

2 Range Sensor Description

The block diagram in Figure 2 shows the major components of the radar sensor system. The sections of the system are the antenna and front end, timing system, DSP based signal conditioning, and mechanical scanner and data acquisition system.

2.1 Antenna and Front End Design

The design of the sensor requires careful attention to the antenna in order to minimize the beam spot size over the range of interest, typically 2.5-15m, while providing a reasonable aperture size for the scanner. A high fidelity simulation followed by verification with a 30cm prototype shows that a Gaussian optic lens antenna (GOLA) is an appropriate method of focussing the beam for use in the ranges of interest. As seen in Figure 1, the verification lens very closely follows the simulation predictions. To make the scanner mechanism more practical, a 23cm lens with slightly greater beam divergence is used on the prototype.

The front end of the system is based on a 94GHz Gunn diode coupled to an Impatt amplifier outputting 250mW maximum. An adjustable attenuator allows for future

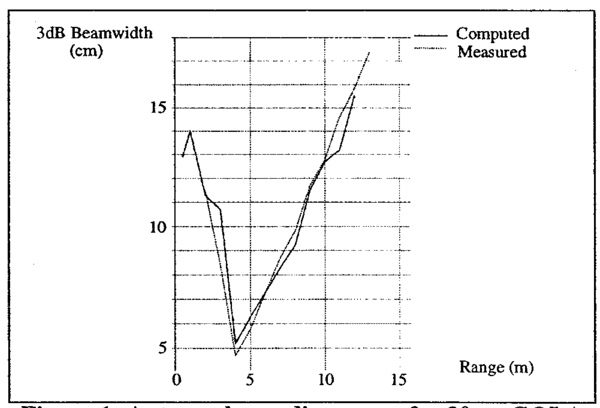

Figure 1: Antenna beam divergence for 30cm GOLA

experimentation to determine the power output requirements of various applications. A high speed switch allows a short pulse to pass through the circulator to the antenna. Returned signals from each target are received through the same antenna and circulator, and are mixed with the transmitted frequency in an I/Q demodulator configuration. An LNA on each channel amplifies the signal to usable levels for the timing system.

A sample I/Q output is shown in Figure 4. The leakage

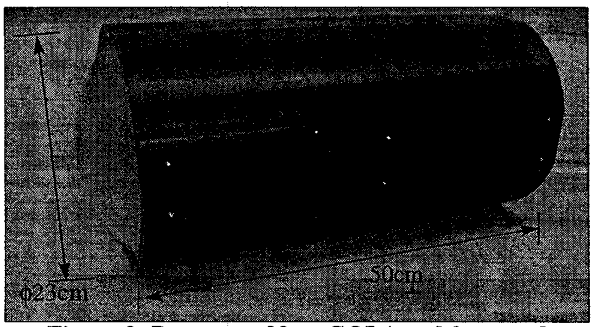

Figure 3: Prototype 23cm GOLA and front end

of the transmit pulse through the circulator effectively blinds the receiver from looking for returns until transmission is complete. In practice however, a period must be allowed for the front end circuitry and amplifier to settle to a fully recovered state before the returns can be reliably sensed. Therefore, a custom high speed switch was designed to minimize the transmit pulse and to provide sharp rise/fall switching times. The switch in the prototype provides a 7ns full width half maximum pulse with 1.5ns switching time. This period of effective blindness, combined with a conservative amplifier settling time, yields a minimum usable range of 14ns (or 2.1m).

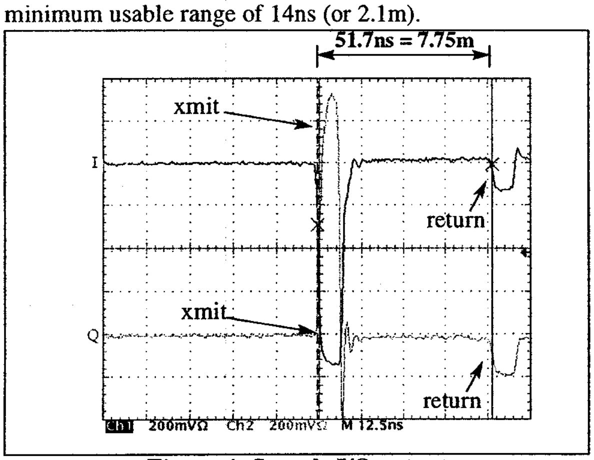

Figure 4: Sample I/Q output

2.2 Timing System and Interface Circuitry

The TOF timing system is based on commercially available nuclear physics laboratory equipment. The leakage of the transmit pulse through the circulator appears as a large amplitude pulse at the I/Q outputs, and is used to start a time amplitude convertor (TAC). To achieve this, the Q signal is split and fed into a level threshold detector based on an AD96685 comparator. The resultant ECL signal triggers a MC10198 one shot which enables the timing system for 400ns. This enable signal is level converted to NIM negative logic using an MC10192 into suitable 50ohm termination at the start input of the TAC.

Additional amplification of the I and Q signals is necessary to meet minimum signal input levels of the prototype timing system. Initial efforts to add a series secondary amplifier to the output of the front end proved troubling due to the large transmit leakage of the circulator. Any amplification attempted was adversely affected by the transmit pulse and was therefore unable to recover in time to cleanly amplify the near range returned pulses 12-18ns later. A high speed GaAs switch was inserted between the primary and secondary amplifiers to prevent the transmit pulse from reaching any secondary amplification. The ECL start signal, after conversion to TTL levels by a MC10125 and delayed by an appropriate time, is used to switch in a secondary amplifier after the transmission is completed. The voltage of the control signal causes a slight bias on the output of the switch, which is compensated for by an adjustable offset voltage fed into the opposite port, or normally closed contact, of the GaAs switch.

The I and Q outputs of the secondary amplifier are fed through splitters into a set of four constant fraction discriminators (CFDs). CFDs are used to minimize the impact of return signal strength on the range reading by relying on the consistent rise time characteristics of the I/Q signals. Since the prototype CFDs are triggered only by a negative going signal, I and Q are each split and one half inverted such that Q, Qinvert, I, and Iinvert are each input to a CFD. The 4 CFD outputs are logically OR'd together, and the resultant signal is used to stop the TAC. The CFDs are disabled from reporting transmit leakage and targets closer than the minimum range by a veto signal generated by delaying the TAC start signal for a short time until the amplifiers and switch have settled out the transmit pulse, currently 18ns in the prototype.

The TAC outputs a 1usec analog pulse with voltage amplitude proportional to the time, and thereby range, to target. A 300ksps 12 bit A/D with high speed sample/hold is used to digitize the range. Under laboratory conditions, the combined error of the CFDs, logical OR, TAC, and A/D in the timing system is 161 ps, which translates into a range accuracy error of 2.4cm.

2.3 DSP Conditioning

Due to the varied reflectance and specularity of targets in the millimeter wave band, DSP processing has been added to the range data stream. The DSP algorithm takes a programmable number of sequential range values, some of which may get no return due to specularity or weak reflectivity of the target, and determines a single data point to provide to the data acquisition system. Several algorithms have been implemented and tested for the DSP conditioning.

- Average - averages *n* points and returns single reading to data acquisition system. This greatly improves accuracy for stationary readings, but scanning two targets in a given set of samples results in a ghost target between the two.
- Nearest - detects the nearest target to the sensor for *n* firings. Does little to improve accuracy, but provides safest result for collision avoidance.
- Biased Median - first sorts the valid range readings, ignoring any invalid returns, then chooses the point one third through the returns sorted by increasing range. By selecting this point, range returns from closer targets are weighted more heavily than those from farther away. Finally, the algorithm averages all points within 0.25m of the chosen point to improve the accuracy of the reading by assuming all such returns are from the same target.

The prototype DSP code samples a data set of 20 firings taken at 250kHz to yield a 12.5kHz systemic data rate. This method provides not only more accurate range data, but also greatly increases the likelihood of seeing intermittently specular and highly diffuse targets over a raw sensor providing the same data rate. For example, a sensor firing at 12.5kHz looks for a target once every 80usec. A DSP processed sensor providing the same data rate to the autonomous system looks for a target 20 times during the same time period, or once every 4 usec. Because the sensor is looking for a return 20 times more frequently, it has a correspondingly higher probability of seeing a target with intermittent returns. Assuming a valid return rate of 50% and a Gaussian distribution of range readings, the ten readings combine to reduce the standard deviation of the single shots by a factor of $\sqrt{10}$.

2.4 Scanner Description

The scanner consists of two orthogonal axes. The scan axis, coaxial to the radar point sensor's axis, is a high speed continuously spinning 45° wedge which is designed to rotate at up to 3600RPM. The configuration allows an unobstructed 180° scan of the reflector. The combination of radar point sensor and scan axis is mounted on a slower vertical pan axis which can pan 360° at rates up to 60°/sec. The pan axis needs only to pan +/-90° to get an unobstructed view of the entire world below the horizon of the sensor.

The reflector is composed of an aluminum honeycomb substrate with a 0.5mm flat sheet bonded to its surface. While the honeycomb structure provides excellent rigidity the flat sheet is needed to provide a mirror like surface to direct the radar beam. Brushless DC motors control both the pan and scan axes. The scan axis uses a frameless motor with resolver feedback while the pan axis uses a more traditional enclosed motor with integral encoder/hall sensing for commutation and position control.

2.5 System Operation

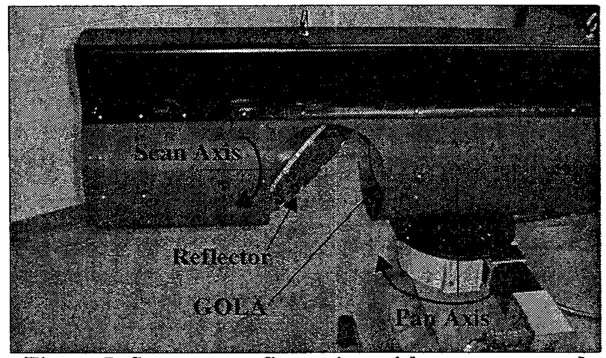

Figure 5: Scanner configuration with cover removed

The scanning system triggers the radar system using a free running variable frequency oscillator. The system as described uses a 250kHz firing rate for the front-end trigger. After 20 firings, the DSP performs the filtering algorithm and triggers the data acquisition system to latch the current values of the scan and pan axes. The combination of range, pan (azimuth), and scan (elevation) angles specifies a unique spherical coordinate in space.

The data acquisition system is PC based and contains interface cards for digital I/O, encoder quadrature, and communications to the host automation processor. Each servo axis is controlled by a motion controller/amplifier combination which connects to the PC via RS232 interface. Commands to the motion controllers are infrequent since both axes are set to perform fixed motion patterns. The encoder from each axis is fed to both the motion controller for each individual axis and the encoder quadrature card in the PC. The DSP interrupts the PC when a valid range reading is available, at which time the acquisition software captures the parallel digital range on the digital I/O board along with the current position of each axis of the quadrature board. This data is acquired at 12.5kHz filtered or 250kHz unfiltered and can then be processed by the rest of the robotic automation system for navigation, collision avoidance, and trajectory generation.

3 Results

The prototype sensor, timing system, scanner, and data acquisition system have been fully assembled and integrated. Scans have been made using a peak scan axis rate of 1800RPM. Ranging results using raw sensor data have shown a +/-15cm accuracy over a wide variety of both indoor and outdoor target environments including vehicles, brick walls, rocks, and dirt.

Initial DSP processing of the data stream has typically provided 50% more valid range data at a systemic sampling rate of half that without the DSP for an apparent tripling of the meaningful data rate. For example, raw sensor scans were taken with a sensor firing rate of 25kHz and were compared to DSP processed scans utilizing a sensor firing rate of 250kHz and data acquisition rate of 12.5kHz. The DSP processed scan contained 50% more valid datapoints than the raw scan. In another test, a target returned 10 valid hits from the raw sensor at 1.25kHz. The same target returned 21 hits using a comparable data acquisition rate and DSP processing. The algorithm's predicted improvement of accuracy has not been analyzed to date.

Figure 6 shows a digital camera view and two views of data taken from a scan of a dumptruck and its surrounding terrain. Each coordinate set formed by an azimuth, elevation, and range reading is translated into a cartesian point in space. The user is able to fly through the resultant model of the environment using a VRML/WRL compatible viewer to verify proper operation of the sensor. The two range maps shown are screen captures of such a viewer. The resultant 2D representation was processed by a "plaster" imaging effect to make the scene more easily interpreted without the motion cues provided by the VRML interface. One can clearly see the straight sides of the truck bed, points on the canopy of the truck, and the surrounding ground. Examination of the scan using the VRML viewer shows even the tire rims and reveals that the points appearing inside the truck bed in the bottom range map view are actually proper returns from the ground below the truck.

The scan shown utilized a scan axis rate of 10Hz and a pan rate of 10°/sec. The scan took approximately 18 seconds to complete, during which time the scanner imaged not only the truck shown, but a full 360° scan of the entire surroundings of the sensor. The system has performed similar scans at 30Hz scan axis and 30°/sec pan rates to generate a comparable image in 6 seconds. DSP processing was not utilized for this scan.

Recognition algorithms previously functional on a similar laser based scanner have successfully located and identified objects in the test radar scans. The truckbed, which actually measures 5.5mx2.3mx1.6m, was located and identified as 6.2x2.2x1.4m in size by the algorithm.

4 Future Work

The SPDT switch and secondary amplifier previously capable of handling the large transmit leakage spikes are greatly reducing the signal to noise ratio of the system. Additionally, the bias voltage for the switch is somewhat temperature dependent. The insertion of a millimeter wave switch before the LO port of the mixers would greatly reduce the impact of the transmit leakage of the circulator. Without such large transmit spikes in the I/Q signals, the SPDT switch between the amplifiers could be removed, and amplifiers that are more appropriate for the low level signals could be applied, thereby increasing the sensitivity and stability of the system.

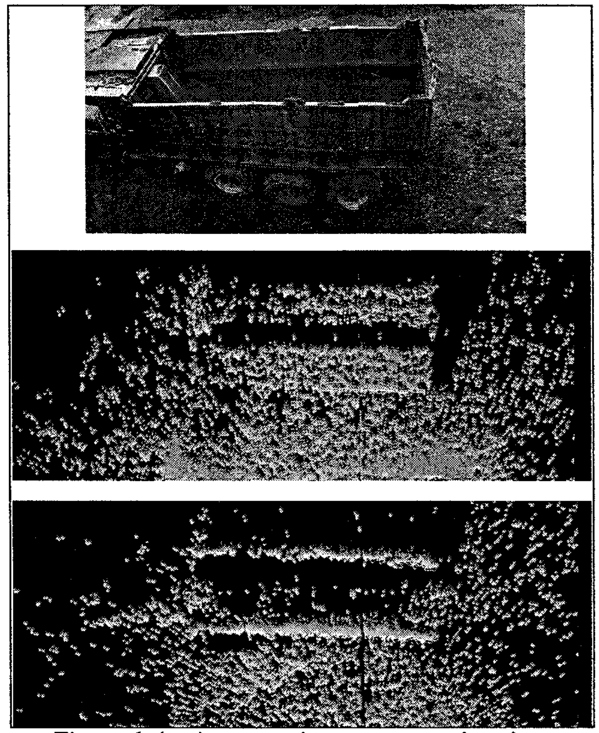

Figure 6: (top) camera image perspective view, (middle) range map perspective view, and (bottom) range map top view

The current timing system is big, bulky, and power hungry, but serves to evaluate the sensing methodology. Future revisions of the sensor will include a greatly miniaturized timing system, most likely on an ASIC.

The data acquisition system is also much larger and more capable than necessary. Future revisions will aim to reduce the size and improve the durability of the system to permit longer term field trials.

The aperture size is driven by the desire to have an effective divergence of approximately 1°. Unfortunately, the aperture size also dictates the size necessary for the antenna and scanner mechanism. Future work will investigate higher frequency operation for a smaller overall unit size.

5 Conclusion

The prototype sensor has proven the viability of high resolution, high speed radar range sensing for autonomous vehicles. Scans taken by the radar system are comparable in data quality and quantity to those of many laser rangefinder based systems, but can be generated under adverse environmental conditions. The ability of such a sensor to robustly sense a workspace in an uncontrolled environment is an enabling technology that needs further development before fully applicable to commercial robotics.

6 References

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