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Short Range Safeguarding for Urban Driving

This report covers the development of a prototype low-cost collision warning system for short-range safeguarding (less than 5 meters) for driving in urban environments. Special interest is placed on using small, simple and cheap smart sensor modules that together, form a distributed sensing network whose overall performance exceeds the sum of the individual sensors. A "safety by the meter" approach is incorporated, allowing the system to fit to vehicles of any size. It will be shown that with common simple ultrasonic sensors and a distributed sensing approach, a powerful sensor system can be formed.

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I. Introduction

This chapter gives a general overview of the project. An analysis of traffic accident statistics leads to the definition of the goals to be achieved and also under which circumstances the system should work. An overview of the experimental setup is also given. This chapter concludes with an overview of the sections covered in this report.

Traffic accidents cause more than 6 million injuries and fatalities[1] per year. Accidents involving pedestrians represent the second largest source of that and children are especially at risk. Legislators and automobile manufacturers are trying to increase the safety of the car's design and its operation. This is done by different means: Different laws aiming at the conduct of the drivers and others forcing the automobile manufacturers to change the vehicle's design in order to lower the impact of collisions. Another, more recent approach to prevent accidents is the use of collision warning systems, signaling the driver a potential risk so he has time to react.

Special interest is also given to transit buses because they operate in restricted spaces and in the presence of pedestrians.

A collision warning system has to recognize relative speed, orientation and the distance between the instrumented vehicle and nearby obstacles (pedestrians, cyclists, other vehicles and static objects near the road). Another issue is the possible influence of environmental factors such as weather, lighting and roadway conditions. In this work, a short-range safety system for the collision avoidance between the car and pedestrians is proposed, but might also be used for detection of any other obstacle or features such as the curb. Detecting the curb can be useful to determine which objects are potentially a danger (those off the curb) and which can very likely be ignored (those on the curb).
Although the weather and lighting aren't explicitly covered from the system, certain robustness is demanded from the system in order to work under most environmental conditions.

Collision warning systems using many different kinds of sensors have been proposed and tested (see chapter II) but few have actually been commercialized. An important criterion for this sensor system is simplicity and especially low-cost. One step in this direction would be to create a system that can be scaled in order to fit any kind of vehicle (from sub-compact personal cars to transit buses and trucks) without changing the hardware or software, but by simply adding some more sensors. This is the safety by the meter approach. This approach is only possible, when the individual sensors are relatively cheap.

Of course such a sensor system can be useful for many other robot applications, especially (mobile) robots that have to deal with the presence of humans, but have limited computational power and have to be cost-efficient.

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[1] Source: United Nations Economic Commission for Europe

Traffic accident statistics

The International Road Traffic and Accident Database [1] maintained by the OECD and covering almost 30 countries (most European countries but also the United States and Australia) reveals that approximately 50% of fatalities happen in urban environments. 23% of the fatalities in the year 2000 have been pedestrians and 6% have been cyclists. Accidents with pedestrians represent the second-largest source of injuries and fatalities. Therefore the development of a sensor system looking ahead and detecting pedestrians before an accident happens is a very worthwhile goal.

Unfortunately the statistic mentioned above does not give a distribution about where the accidents happen (on intersections, off the road) and which part of the vehicle was involved (side-collision, front-collision). Another evaluation of accident statistics for transit buses done in the Navlab [2] reveals some of these details:

- Buses are 15 times less involved in accidents with fatalities per passenger mile traveled, but they have 15 times more collisions per year.
- Even though buses hit other vehicles or objects 25 times more than pedestrians, the percentage of fatalities in bus-pedestrian collision is fairly high.
- Most accidents involving pedestrians happen on the roadway and on the crosswalk at intersections .
- Most collision with buses happen on the side (75%) and the rear (15%)
- Cyclists often get squeezed between the bus and other vehicles while being passed by the bus.
- Speed in urban areas is in generally low (less than 30mph). In accidents involving pedestrians the average speed is 20mph.
- The pedestrians are mostly walking, though some special cases exist, where the pedestrian was not moving. With bus-pedestrian collisions almost 25% of the fatalities occur with the persons partially or completely underneath the bus.
- Weather, lighting and street conditions, age of the involved driver and/or pedestrian aren't a measurable factor

As mentioned before, there is a strong interest in developing a sensor system that is capable of distinguishing between living and dead matter. This is especially useful as a pedestrian's action is much harder (if not impossible) to foresee. For example, a car is much more likely to stay on the road, whereas a pedestrian can change his path within a moment. As the bus-pedestrian collisions with the pedestrian partially or completely under the bus often result in fatalities, and no sensor system dealing with this situation has yet been proposed, the possibilities for preventing these situations have to be studied.

Goals

The sensor system covered in this research must ideally achieve the following goals.

- Short-range
- Low-cost compared to other sensors used for vehicle safety
- Small and light-weight (nowadays vehicles are very packed)
- Versatility: The same sensor system should offer the possibility to be used for different applications (looking under the bus, detection of the curb)
- Low false alarm rate

The low false alarm rate simplifies the integration into of the system into a warning system (the interface between the driver and the safety system) as false alarms might annoy the driver which could result in the driver ignoring the system, making it useless.

Some restrictions arise due to the conditions of low-cost and very short range: The system will only be fully functional at rather low speed, in order to have enough time to warn the driver in case of a dangerous situation. These low speed scenarios include mostly:

- Parking
- Accelerating or braking at intersections, cross walks and traffic lights
- Busses at bus stops
- Driving out the drive-way

These scenarios suggest that short-range could be defined as approximately 5meters, because

- If mounted on the side of a vehicle, pedestrians further away than this distance will supposedly be at no risk
- For urban driving, next to the sidewalk are houses, gardens, fences which limit the range of the sensor in any case
- For parking, driving out a driveway, or for busses at the bus stop, a range of more than the distance mentioned above, will in most cases not be very useful, as very fast approaching objects will be detected too late and the warning time will be too short.

Experimental setup

Due to the relatively short time of this project, the sensor modules lack onboard intelligence. This is provided by a centralized standard PC equipped with a data acquisition card (see Appendix II.) sampling at 500000 Samples/second. Although this is quite bulky and not very cheap, real-world tests are easily performed, and the proof of concept of the distributed sensing algorithms is given.

In a second step this setup is mounted on Navlab 11 in order to perform some tests under real-world conditions. Navlab 11 is the most recent research platform of the Navlab group, built around a Jeep and incorporating onboard computing and sensing. The following figure shows the research platform.

Figure 1: Navlab 11

There are SICK[2] laser scanners on each side, with a third one mounted on the front bumper. The front bumper also contains an omni-directional camera, a laser line striper for curb detection and a 180° field of view camera system. There is a side-looking camera for each side. Furthermore the car is also equipped with an inertial navigation system and GPS.

Organization of the development

The organization of this work has been done in the following steps, which is also mainly adopted for the structure of this report:

1. Analyze Incident data
2. Establish goals for sensor system
3. Assess existing systems
4. Select the most suitable techniques
5. Construct a prototype system
6. Test prototype system
7. Propose modifications for pre-series prototype

The first two points are covered in this chapter, the third one is covered in the chapter about the related research, the fourth point is covered in chapters III (single sensor module) and IV (distributed sensing). Chapter V covers different applications and the corresponding results from these real-world tests. The conclusion contains modifications for the next generation sensor modules (chapter VI).

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[2] http://www.sick.com/, last visit 19-02-2003

II. Related Research

Due to the magnitude of the problem with traffic accidents, there is a lot of academic and industrial research in collision avoidance systems. After the mostly highway oriented research of the past and as sensors and computers get more powerful and versatile, the urban areas, which are far more complex and a bigger source of incidents, is now targeted. Vision systems are very often used and also laser range finders are more and more commonly employed. Radar as well is a common sensor often replacing the well known ultrasonic sensors but much more expensive. This chapter is structured by the different sensor modalities, followed by the research in the distributed sensing and sensor networks.

General approaches

The European Union studies research going towards safer cars, e.g. for lowering the maximum tolerated impact coefficient for a vehicle hitting a person, forcing the automobile constructors to adapt their cars for more safety. Although an important measure to avoid or lower the impact of accidents, sensors should be used as a complement for such measures in order to have a maximum effect by avoiding the accidents in the first place. Another suggestion is to make the roadways and vehicles more sensor friendly [3], by using for example, license plates and other geometrical structures with a high radar reflectivity or by using fluorescent lane and obstacle marking in order to simplify detection.

Vision

Many groups using vision for obstacle detection are using stereo systems [4], [5], [6], [7]. There are some special constellations, such as an omni-directional stereo system [8] or systems using simple linear cameras [9], [10], [11] where especially the linear cameras have the possibility to be low-cost sensors, but the calibration issue on these makes them very difficult to use, although there is some research, trying to make this process simpler [12]. More recently, some research groups are focusing on the urban areas and especially for pedestrian detection using vision systems [13], [14], [15]. Others are using additional sensor modalities and sensor fusion for better detection [16] and [Navlab]. Another vision approach is using the optical flow [17] for object tracking [18], [19], [20], some paired with stereo-vision [21].

Radar

Radar has many advantages such as long range, fast detection and its robustness in diverse weather and lighting conditions and is used in many collision warning systems in (automotive) research laboratories [22], [23], [24]. It also has several drawbacks, such as relatively high cost, possible interference with several sensors, important minimum distance. Radar is commercially mainly used in another vehicle safety issue, which is the adaptive cruise control. Due to the wider application range of radar especially in automotive applications, it can be expected that the cost will be lower in the near future.

Laser rangefinder

Some systems are using a horizontal laser rangefinder in order to detect obstacles. These sensors, commercially available have a very high resolution, but are quite expensive. A novel Laser line striper has been developed in the Navlab, used principally to detect the curb [25].

Other sensors allow three-dimensional scans, but are prohibitively expensive and produce a significant amount of information to be processed.

Ultrasonic sensors

Radar sensors, now often replace ultrasonic sensors as one of the simplest and cheapest rangefinders. There is still ongoing research, but tending to more sophisticated configurations than the relatively simple and well-known time of flight measurements. In order to overcome the bad bearing characteristics, some use echo location (like bats) [27], [28]. Others use multiple sensors, but this may cause interference that can lead to a high number of false readings. In order to overcome this problem algorithms have been proposed in order to reject most false results [29]. Another approach is to apply radar techniques to ultrasound, which allows pulse compression, detection of several objects and identification of each sensor's echo by modulating an unique code onto the chirp [30], [31], [32], [33], [34]. It is also possible to use ultrasonic information for a basic target classification in terms of surface [35], or basic shapes like corner, edge and surface [36], [37], [38]. The fact that low-frequency signals easily diffract around an object is used to detect partially occluded objects [39].

Person detection

The most common sensors for person detection are vision systems with conventional cameras or thermal infrared imaging cameras for better discrimination between warmer (living) objects and colder objects (environment) [40]. Others use additional sensor modalities such as radar [41] or audio and laser range finder [42]. Audio is not appropriate for outdoor use, especially near a road where the acoustic noise is far too complex to detect persons (especially since not everybody is talking). An uncommon sensor system was proposed by the MIT MediaLab [43], using an electric field to detect persons. It would be very difficult to use it outdoors on a moving vehicle, where the conditions change all the time. No work was found dealing only with simple and cheap near-infrared devices such as pyro-electric sensors or thermopiles.

Distributed Sensing

Distributed sensing is a fairly new field of research and many algorithms are studied in order to help to understand how limited resources can be shared in a optimal way. Although this is important for sensor networks dealing with hundreds or even thousands of sensors, it can be assumed that for a small number of sensors (maximum some dozens), every single one of them has its own (and sufficient) resources.

Another application for merging information of a lot of different sensors and sensor systems lies in the military sector for tracking targets [44], [45], [48]. A project dealing with distributed sensors [46] uses mobile robots, where only the fusion of all robots' sensors together contributes to useful information. The dynamic reconfigurable aspect of systems is also investigated in small robot systems, which only together can achieve a high-level goal [47]. A more novel approach such as "safety by the meter" was not investigated yet. On the low-level area, dealing with issues such as the actual connections and network protocols, the IEEE has established a standard [49], pointing towards "smart sensors", with the goal to simplify the connections between different transducers and a given system and allow dynamic reconfiguration. As this is purely an architectural topic, it will not be covered in this report.

III. Description of a sensor module

This chapter begins with the choice of the sensors for a single module followed by a detailed description of its hardware, software and processing algorithms. First there will be the description of the ultrasonic part, followed by the person detector part. Some results obtained by testing such a device will be found at the end of this chapter.

There are many different types of sensors and sensor systems (vision, radar, ultrasound, IR, laser) in different constellations (directional and omni-directional) and based on different principles (active versus passive sensors). A short comparison between these sensors can be found after the general considerations.

III.1. Choice of sensors

There are several topics to be looked at in order to choose the right sensors, as presented in the following paragraphs.

III.1.1. Active versus passive sensors

Active sensors may cause interference between cars equipped with the same sensors leading to a possible loss of information. This can be prevented by several measures, such as an intelligent firing schedule or sending an identification tag with the outgoing signal. With the latter solution and using signal processing algorithms, interference can be detected and even used as additional information. Another possible and interesting issue could be inter-vehicle communication using the information contained in the emitted signal, forming a big sensor network which actually would extend a single vehicle's range of vision to that of all vehicles in its neighborhood resulting in an eventually shorter warning time.
Passive sensors are in turn more dependent on the environment. Cameras, and especially the corresponding processing algorithms must deal with many different lighting and weather conditions such as snow, rain, sunlight, city light, night and clouds and fog. On the other hand, passive systems are in general less power consuming, which basically is an advantage for automotive products.
Because an urban environment is highly dynamic, an active solution is preferred.

III.1.2. Distributed versus centralized computing

There are several reasons opting for distributed computing, e.g. every sensor module has its own controller.

- Bandwidth of network
- Speed
- Plug and Play
- Robustness
- Range Resolution

First, the bandwidth of the network can be significantly reduced when only processed instead of raw data is sent and received between the modules and / or between the modules and a master computer. Secondly the emerging parallelism might speed up the processing of all data, especially if many sensors should work together. And third, on board intelligence allows dynamic reconfiguration. This, in turn makes the system more robust. If a module fails, the network performance only degrades instead of failing completely.

III.1.3. Directional versus omni-directional

At first sight, omni-directional devices seem to be the better choice (as everything, or at least a large portion of the vehicle's perimeter should be scanned). But the form of the vehicles imposes, that omni-sensor can't be mounted in a way that there are no dangerous dead angles. If mounted on the roof, there is no coverage of the area near the vehicle (especially for busses). Therefore several sensors have to be used for full coverage. Also the information of directional sensors is in general easier to treat and therefore computationally more efficient.

III.1.4. Conditions for choosing a sensor

The main conditions for choosing the appropriate sensors are in this report, excluding the reasoning of the paragraphs above:

- Small size (nowadays cars and vehicles are already packed and no extra space can be spared)
- Low weight
- Robustness
- Frame-rate (must detect possible dangers in time for a warning and reaction of the driver)
- Low-cost. This applies not only to the cost of the hardware, but also to the integration cost (packaging, wiring), especially as multiple sensors might be needed for a vehicle (depends on its size).
- Simplicity, in order to prove rapidly the concept of the distributed sensing algorithms

Also a sensor combination which permits to track not only static and moving objects, but which also helps to discriminate whether the object is a human seems to be necessary. In order to evaluate, a detailed comparison between all considered sensor modalities has been established (see table below).

Table 1: Comparison of sensors

	Ultrasonic sensor	Radar	Sick Laser Scanner	Structured light	Linear Camera	Camera	Infrared Imaging Camera	IR sensor (thermopile)	Pyro element	Capacitive sensors
Size	++	+	-	-	+	+	-	++	++	-
Cost	++	-	--	-	+	+	--	++	++	++
Range	+	++	++	+	+	+	+	+	++	-
Resolution (distance)	-	+	++	+				-	-	+
Angle of view	-	-	++	+	+	+	+	-	+	
Weight	+	+	--	-	+	+	-	++	-	-
Calculus power needed	++	+	-	-	-	--	--	+	+	+
Power	+	-	--	-	+	+	+	++	++	++
Framerate	+	++	++	+	+	+	+	-	-	+
Commercially available	+	+	++	-	++	++	+	++	++	+
Robustness	+	++	+	+	+	+	+	+	+	-
Discrimination human / non human	-	-	-	-	-	+	++	+	+	-
Advantages	Low-cost, simple, small	Range	Accurate, fast, fully implemented, Wide angle of view	Camera information can also be used for other processing	Small sensor, much less information than standard camera	Same information as used by human drivers. Possible use of stereo and optical flow	Simplified person detection.	People detection only	People detection only	Very cheap and easy to interface. Might be used to look under a vehicle
Inconvenients	Sensitive to air conditions (turbulences). Scattering	More expensive.	Very expensive. Not designed for dynamic use	Big. Calibration. Expensive filters, fast shutter	Calibration for stereo-vision is very difficult to achieve.	Computational expensive. Sensitive to lighting conditions	Very expensive	Hotspot detection difficult	Reacts only to movements (of either the vehicle or the heat source or both)	Only for very short range. Very sensitive to environmental conditions

Comparison results

This comparison and the conditions mentioned above favored for the person detection part clearly a passive infrared mainly for its low-cost and simplicity. The studied thermopile used for example in contact-less thermometers returns the average temperature in its field of view, making the detection of a hotspot such as a pedestrian in a scene very difficult. This can be solved by using small field of view sensors, so that a human covers a large part of the scene even at longer distances. Pyro-electric sensors, used often in alarm systems or remote light switches, only react to movement, but cover a much larger field of view.

As integration cost can't be neglected, the size, weight and power requirements of the sensor is an important factor and eliminates, in conjunction with the material cost, many solutions, leaving basically the ultrasonic sensor in order to achieve most of the above mentioned goals. The main disadvantage of this sensor modality is scattering, which appears when the sound wave hits a target under a relatively big angle, so that the wave is not reflected back to the sensor. In outdoor environments this effect is less significant, as many obstacles are not flat, but present angles, corners, etc. The second drawback, caused by turbulences of the air, is especially important at higher speeds, where a short-range system looses its effectiveness anyway.

In general the common time of flight measuring ultrasonic sensors have very bad bearing resolution. Also, mostly only the nearest target is tracked, as in general the detectors only integrate the return signal and respond above a certain threshold. Another issue is the echoes from multiple reflections that often induce false results.

On the other hand, ultrasonic sensors have important advantages when properly used:

- Using more than one sensor, triangulation can be used for much higher bearing resolution (position can be calculated in up to 3 dimensions).
- Using short pulses or radar technology such as pulse compression, the depth resolution can be improved.
- Doppler effect can give additional information about the speed of the objects.
- Coding each sensor's emitted signal with a unique sequence can be used not only to reject interference (known as cross-talk) but also to use it as additional information.

- Using a coded signal and changing the codes from one cycle to the next one, the sensing range can be precisely limited which makes the system more robust against multiple echoes (which often lead to false alarms)

The chosen combination of the pyro-sensor and the ultrasonic sensor provides an extreme low-cost sensory system.

III.2. Description of a sensor module

A sensor module consists of two complementary sensors: An ultrasonic distance sensor and a pyro-electric near-infrared person detector as used in diverse household and alarm systems. Each of these subsystems is presented in terms of hardware as well as in terms of signal processing algorithms in the following paragraphs.

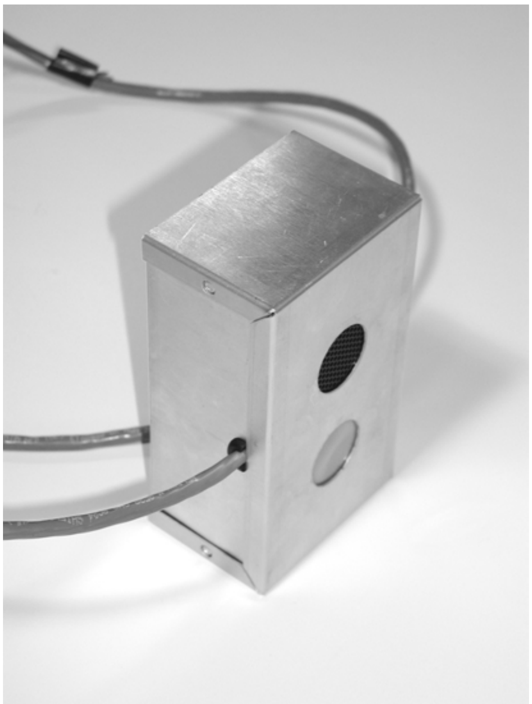

Figure 2: A sensor module, showing an opening for the ultrasonic sensor (above) and the Fresnel lens for the infrared detector (below)

III.2.1. Ultrasonic sensors

The ultrasonic sensors used for this project are the Polaroid 7000 series electrostatic transducers using custom electronics (Appendix I.). Technical specification of the transducer can be found in Appendix II. Each transducer serves as transmitter and receiver, which lowers cost. However, while sending the sensor is not capable to receive, which imposes a certain dead zone.

Pulse coding

In order to identify each sensors chirp, an identification tag has to be modulated on each emitted chirp. This is not only advantageous for multi-sensor applications because it increases the signal-to-noise ratio, it also gives the possibility to limit the sensing range and helps to detect and discriminate several objects in a scene. For the multi-sensor configurations the coding helps to reject interference, respectively allows using this cross talk as additional information. In order to find the best coding scheme, the most promising have been tested under real-world conditions:

- Frequency modulation (FM)
- Amplitude modulation (AM)
- Phase shift modulation (PM)
- Pulse shift keying (PSK)
- Pulse length modulation

In order to find the signal again in the received signal, matched filters are often used ([30], [31], [32], [33], [34]). They basically perform a correlation of the received signal with a template of the (known) emitted signal. When the sent signal has a sharp autocorrelation function, this filtering will result in a sharp peak at the position where the received and the emitted signal match best. In radar technology, this is called pulse compression. Using conventional time-of-flight measuring sonar, two or more objects cannot be distinguished when they are so close to each other, that their individual echoes overlap.

Matched filtering was used for the FM, AM, PSM and PSK modulation. The best correlation results are directly dependent on the usable bandwidth and the length of the pulse. All modulation schemes (except the pulse length modulation) have been simulated and tested under real world conditions using the driver electronics and the Polaroid transducer. The mostly very good results from the simulation could not have been confirmed with the real equipment.

Continuous frequency modulation uses the whole bandwidth of the transducer and sends a signal composed of a chain of sub-signals each with a different frequency defined by pseudo-random sequences.

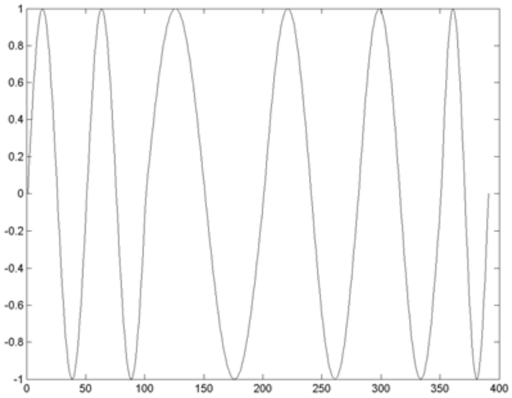

Figure 3: Continuous frequency modulation (exaggerated for better visibility[3]*)*

A simpler schema uses only a fixed number of possible frequencies

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[3] The figures showing the modulation schemes do not represent the real data in order to show the differences between them much clearer

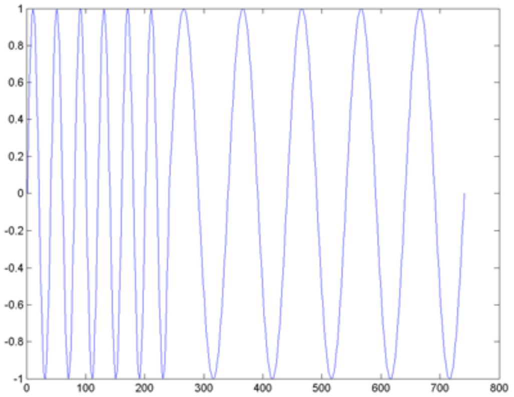

Figure 4: Discrete frequency modulation (exaggerated for better visibility)

The amplitude modulation coded ones by transmitting during several periods at the transducers resonance frequency and zeros by not transmitting at all during several periods.

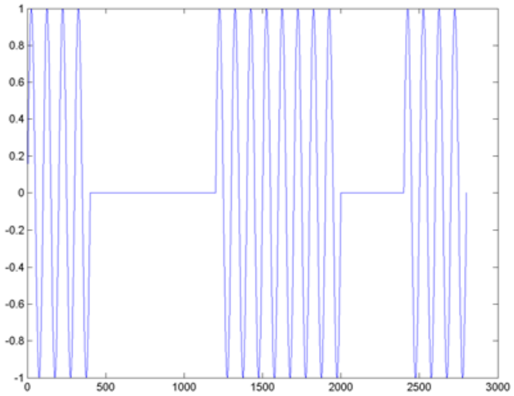

Figure 5: Amplitude modulation

The phase shift modulation is always transmitting at a fixed frequency, but using a 180° phase shift for coding.

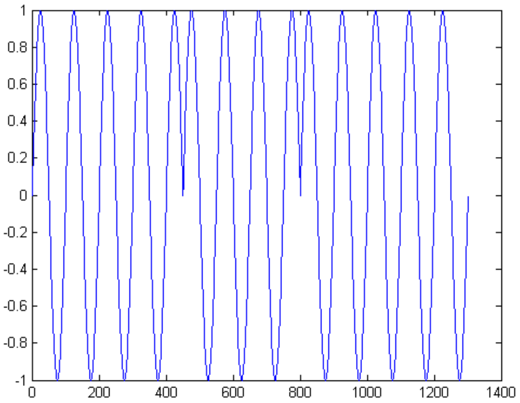

Figure 6: Binary Phase Shift Keying

The pulse length modulation simply has different chirp-lengths for each sensor. Though this as one of the simplest solutions represents at the same time the highest false detection rate, as overlapping echoes cannot be distinguished.

Finally the pulse shift keying codes its information in the precise spacing between two pulses. The table below shows an overview of the performances of the different modulation schemes and will be followed by an evaluation and a final choice.

Table 2: Comparison of coding schemes (see paragraph below for more details)

Coding scheme	**Description**	**Advantages**	**Disadvantages**
Continuous frequency modulation	Uses a pseudo-random sequence covering the whole bandwith of the transducer (30kHz-70kHz)	Theoretically very sharp cross-correlation function. Pulse compression easily possible	Needs more sophisticated electronics to be less dependant on the polaroid transducer's resonance.
Discrete frequency modulation	Uses some fixed frequency parts as bits	Less than above	Simpler than above
Amplitude modulation	Uses on / off state as bits	Works at the resonance frequency. Signal can be extracted	Long pulses needed, resulting in a high computational cost
Phase shift modulation (BPSK)	Uses delayed / non-delayed waves as bits	Very sharp cross-correlation function. Works at the resonance frequency	Computationally expensive: Sophisticated signal processing
Pulse shift keying	Uses the distance between 2 consecutive pulses	Very short pulses needed. Less explicit side-lobes. Works at resonance frequency. Doppler effect can be used. Computationally efficient. Uses less energy than all other schemes.	Doppler effect limits usable bandwidth.
Pulse length modulation	Uses the lengths of pulse trains for identification	Very simple. No need for correlation / matched filtering at all. Works at resonance frequency	Overlying echoes cannot be processed

Comparison results

The continuous frequency modulation with pseudo-random sequences gave the best results in the simulation, but using the given electronics and transducer, the real-world tests were not satisfying. The transducer's resonance frequency is in the center of its relatively wide pass band (see specifications). Also the driver electronics, based on the Polaroid design is primarily designed to work at this frequency. So each frequency transition excited the resonance frequency, which resulted in a signal of 50kHz (the resonance frequency) burying the emitted signal and making it therefore very difficult to detect.

Better results were obtained [32], but using different driver electronics with expensive high-voltage amplifiers and Digital-To-Analog Converters, which are not suitable for this application.

As the transducer needs some time to set up for a new frequency (several periods) another way was sending longer same-frequency bunches in order to stabilize the transducer (discrete frequency modulation). This already ameliorated the results, as the signals could already be easily extracted from the sampled sequence. Though when using several sensors, it is very difficult to distinguish between different codes (the matched filters for each code were too similar).

The use of a modulation scheme working on the transducer's resonance frequency (which also results in higher energy pulses) is inevitable. Though amplitude modulation does not seem to be a very appropriate modulation for sound waves, tests have shown, that with a sufficiently long chirp, detection was possible, even between different sensors if the codes were appropriately chosen.

The binary phase shift keying worked best in the real world experiments, even with several sensors together, but the computational cost was also the highest of all proposed schemes.

The pulse length coding is the very simplest scheme, not needing any complicated filtering but is also prone to most errors and overlying echoes cannot be detected.

The pulse shift keying proved to be very appropriate, having many advantages especially its efficiency, which is mainly due to the fact, that only one filter is needed, even when several sensors have to be processed (the base signal is the same for all sensors, as only the time difference between two such base signals contains the information, which is very efficient).

In this system, the pulse shift keying with ultra short pulses will be used. In fact a single pulse on the driver electronics leads to about 5 oscillations of the transducers membrane which corresponds to a pulse length of 100µs, which at a speed of sound of 343m/s corresponds to an approximately resolution of 1.7cm without pulse compression.

Doppler effect

The time between two pulses of a sensor's chirp will be slightly lengthened or shortened depending on whether the target is moving away or is coming nearer. As the information in the chosen modulation scheme is buried in the precise time difference between two pulses, the Doppler effect actually limits our bandwidth, when this effect should be tolerated by the system. The Doppler shift can be expressed as ([50] and [36]):

$$\Delta t = \frac{2 \cdot \tau \cdot v}{v_s}$$

Where τ time between two pulses, v relative speed between sensor and target, v_s speed of sound. Note the factor 2 because the wave has to be transmitted and received.

The carrier frequency of 50kHz will not be changed significantly and can therefore be considered as constant.

Short-range system does not deal with fast moving objects, as the warning time for a collision with a fast object would likely be lower than the reaction time of the driver. So a system with a range of approximately 5meters and a desired warning time of more than one second before a collision gives us a maximum speed between vehicle and obstacle of 2.5m/s whose Doppler shift must be tolerated (this still corresponds to the considerations made in chapter I).

Now the spacing between two consecutive pulses is between 200µs and 1000µs. As a single pulse on the transducer causes multiple oscillations, the lower boundary guarantees a clear separation of two pulses. The upper boundary has been found experimentally so that the pulses are still highly correlated: It can be assumed that both pulses go through the same

changes and are still very similar upon reception. This fact is used to find the double pulses in the received signal, as their amplitude can be considered equal.
This and the maximum speed lead to Doppler shifts of 2µs and 12µs respectively. As the maximum sampling rate of our system corresponds to a time resolution of 2µs, the system is not able to provide accurate speed measurements. In order to cope with the Doppler shift and the finite precision of the data acquisition, a certain bandwidth for each code will be tolerated.

Signal Processing

In most of the recent ultrasonic related works ([30], [31], [32], [33], [34]) matched filters are used in order to find the coded signal in the received sequence. But this technique is computationally very expensive, as the number of operations for the direct convolution is in the order of magnitude of n^2 for a signal length of n samples.
This becomes very significant for large signals: A sampling rate of 500000samples per second and a range of about 5 meters result in a signal length of ~10000samples. The number of operations needed is therefore about 10^8 per measurement cycle. Even with the fast convolution algorithm (using the Fast Fourier Transform) this is only reduced to about 10^6 operations. Another saving is possible, when processing only a thresholded signal. Also the computationally expensive matched filter can be replaced with a more efficient filter.

The pulses are very short: Approximately 100µs, which corresponds to 1.7cm spatial resolution. If this resolution is considered sufficiently, no pulse compression is needed.

In order to find the most appropriate and efficient filter, the signal has been analyzed and the pulse shift keying can be seen as amplitude modulated signal with the ultrasonic frequency as the carrier frequency multiplied with a lower frequency signal.

$$s(t)=a(t)\cdot\sin(w_c\cdot t)$$

With a(t) a low frequency amplitude modulation function and w_c the ultrasonic carrier frequency.

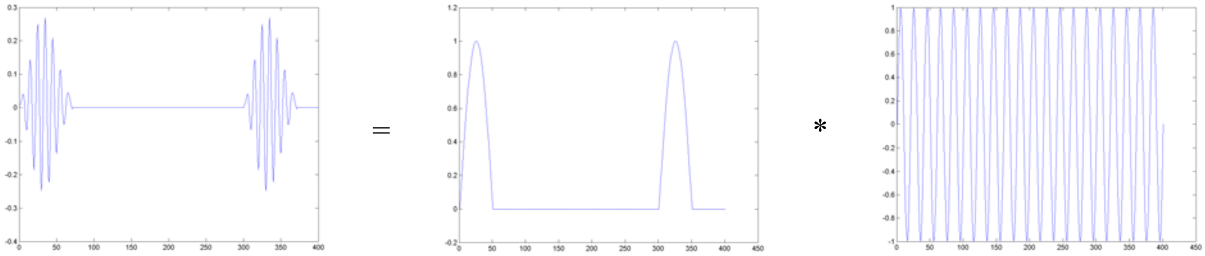

Figure 7:The pulse shift keying modulation scheme

In order to find the pulses again, which are coded in the amplitude function a(t), it is sufficient to apply a simple low pass filter. Here, an efficient order 2 IIR filter has been implemented (the low order leads to very few operations). Secondly the filter is only applied where the signal exceeds a certain threshold. Experiments have shown that setting the threshold to three times the standard deviation of the noise leads to good results.

The signal is sampled with 16bits in order to have a high dynamic range as the intensity of the return signals diminishes very rapidly and is highly dependent on the nature of the reflective surface.

The following figures show each step of the signal-processing algorithm in detail.

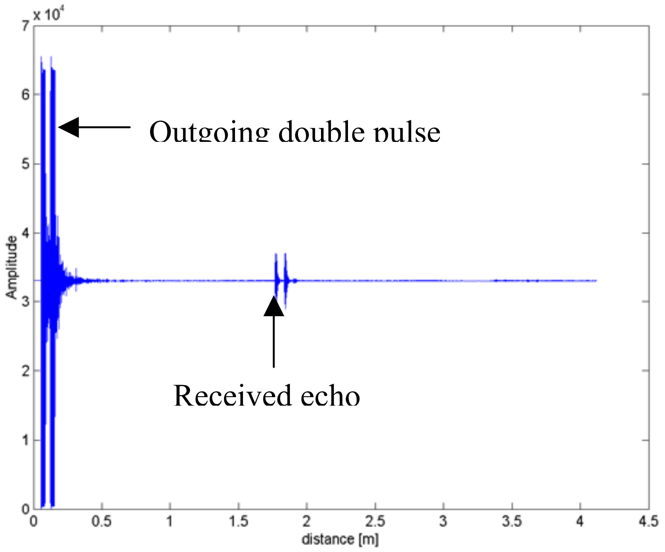

Figure 8: Raw signal[4]: The double pulse at the left corresponds to the outgoing signal (as the sensor serves for both transmitting end receiving). At 1.8m an obstacle can be observed.

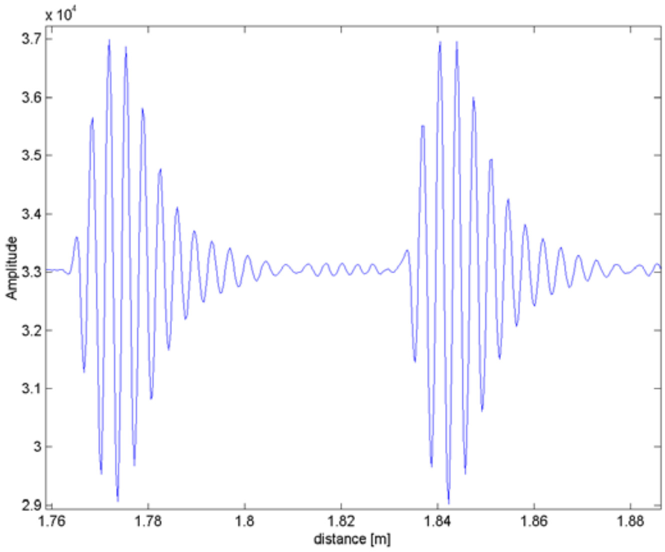

Figure 9: Close-up of the echo in order to show the ultrasonic carrier frequency

Threshold

The first step in the algorithm is to apply a threshold. Because the multiple oscillations of the transducer's membrane cause the analog-to-digital converter to saturate, a non-constant threshold is applied.

The 700µs after the end of the pulse has been sent, the threshold corresponds to a constant, determined experimentally. After that time, the threshold for the rest of the signal corresponds

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[4] The amplitude of the figure corresponds to the dynamic range of the AD converter (5V equals 65384 with 16bit resolution).

to three times the standard deviation of the noise. This has also been determined experimentally and rejects most of the noise. The part of the noise that is not rejected by this means, will be efficiently eliminated in another step of the algorithm.

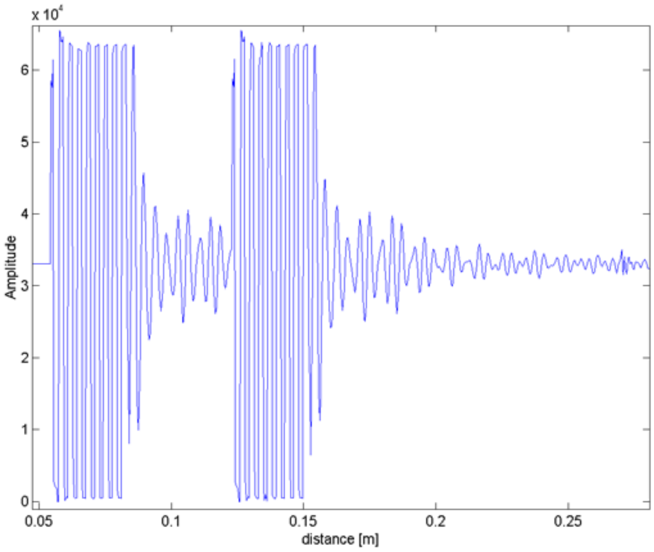

Figure 10:The outgoing double pulse, and the remaining oscillations of the transducers membrane

Zero centring
After the threshold operation, the signal is zero centred and the absolute value is taken. As the main interest is in the low frequency part of the signal (the envelope), the is the first step to extract this information.

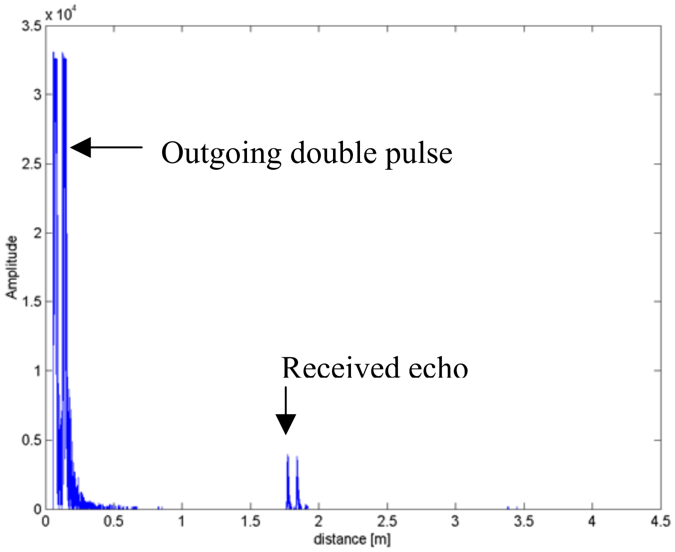

Figure 11: Absolute value and zero centred signal with threshold applied (Note that most of the signal is zero and will not be processed any further)

Filtering
The signal is filtered with an IIR (infinite impulse response) filter of the order of 2 in order to eliminate the 50kHz carrier frequency.

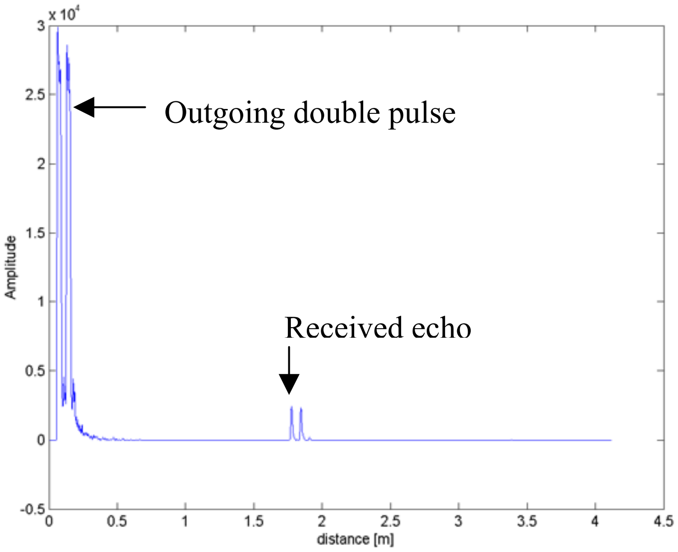

Figure 12: Filtered signal.

Sub-sampling and peak detection

The exact peak detection uses a coarse-to-fine algorithm: First the filtered signal is under-sampled. As the low frequency signal of the amplitude modulation corresponds to approximately 1kHz to 5kHz, a sub sampling by 10 is implemented. Within this signal, the local maxima are extracted. A peak or local maximum is defined by a changing in its slope from positive to negative. Due to the under-sampling, the position is not very accurate. That's why the rough position will be used to search the exact peak position and amplitude in the normal sampled signal.

The result of this operation is a list of peaks, defined by their amplitude and position. Peaks caused by noise are also extracted, but they are eliminated during the next step.

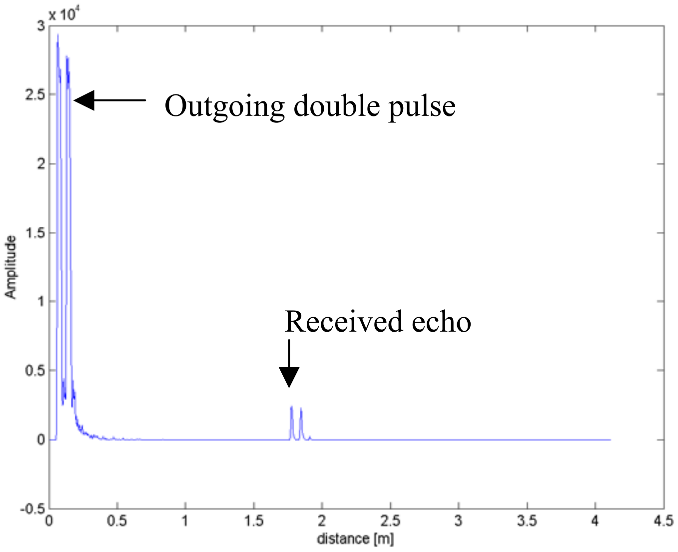

Figure 13: Under-sampled signal, the peaks still appear very clearly, although the maximum's position might no longer exactly correspond to the position of the original signal

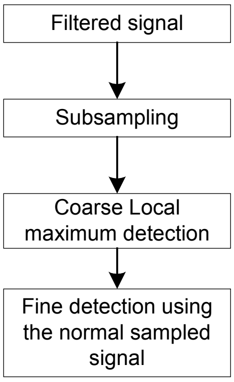

Figure 14:The coarse-to-fine peak detection algorithm

Code matching

The list of peaks is then further processed in order to find matching pairs based on the used code. A certain bandwidth is allowed, permitting Doppler shifts and errors due to the measurement hardware.

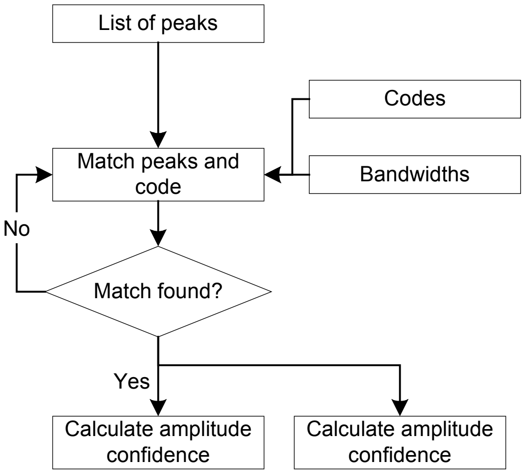

Figure 15:The code matching algorithm, bandwidth needed to accept Doppler shifts

This step already eliminates almost all peaks caused by noise. The matching peaks are also tested whether they have the same amplitude (as the time between them is very small, it can be assumed that they are highly correlated and are therefore subject to go through the same changes in space and time). Only peaks with similar amplitudes are processed any further (the contrary case can also be used when using several sensors, see chapter IV.2 Adaptive firing schedule).

The figures below summarize the whole algorithm:

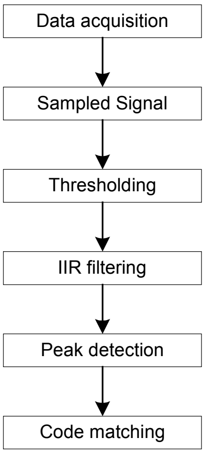

Figure 16:The overall signal processing algorithm

Active range limitation

Sometimes a sensor might receive an echo of a pulse after several reflections. If it is received already in the next measurement cycle, this can cause false results. It is not possible to prevent receiving such echoes, but a very simple measure can cope with some of them. By applying a different code for each measurement cycle, the range can be controlled, as received echoes traveling more than the imposed range will simply be ignored. As the sensor must not wait until supposedly no more echoes will follow, the frame-rate is only limited by the range.
This is especially useful, when the range of the sensor is very short (for example, when a very close object has to be tracked).

The figure below shows schematically the algorithm:

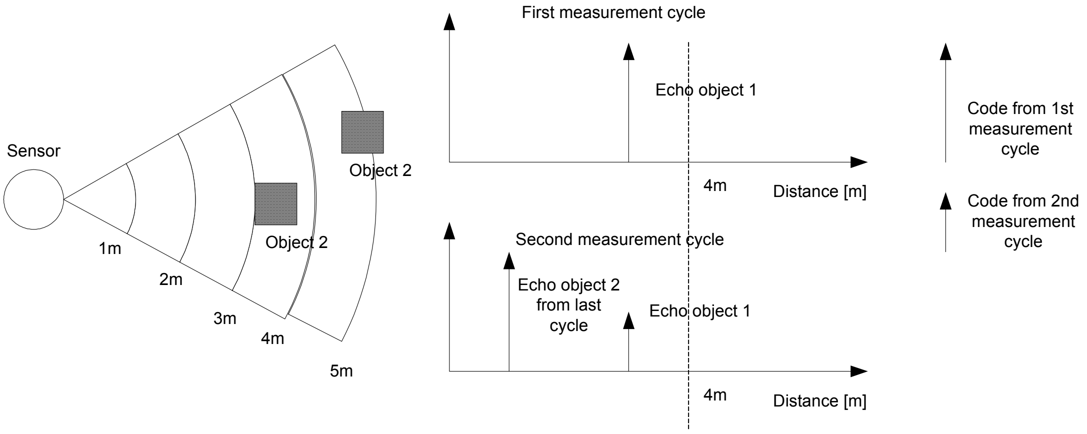

Figure 17: Schema of active range limitation algorithm

III.2.2. Person detection

Except for alarm systems, automated light switches for garden and houses, pyro-electric devices are seldom used for robotics. These sensors are very sensitive, very cheap and robust. A pyro-electric sensor consist of crystalline material that generates a surface electric charge when exposed to heat in the form of radiation. The employed sensor has a filter for the near-infrared radiation from 8 to 14µm, which is approximately the peak radiation of humans.

The sensor used has two sensing elements connected in a voltage-bucking configuration thus canceling signals caused by vibration, temperature changes and sunlight. A heat source passing in front of the sensors will first activate one element and then the other, whereas sources activating both elements at the same time will be ignored. This is also a disadvantage, as static heat-sources cannot be detected. However this is also a special case, which corresponds to a non-moving car and a non-moving person, which is only a problem when a person is already under the vehicle.

A cheap plastic Fresnel lens designed for near infrared wavelengths is used to narrow the field of view of the sensor to approximately 20°.

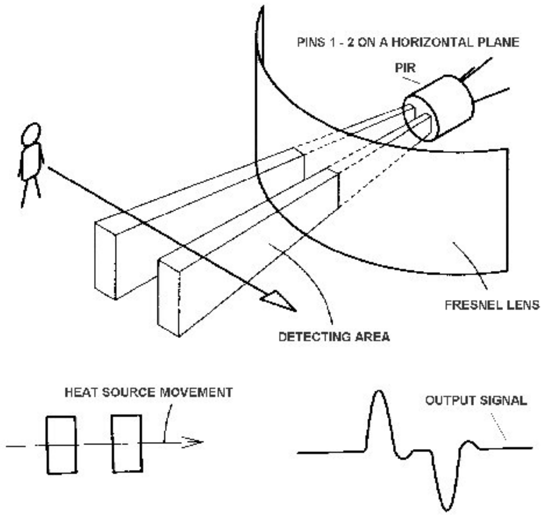

Figure 18: Functional schema of the employed pyro sensor (Courtesy of Glolab)

As can be seen on the figure above, the double element provides additional information about whether the target moves from the left to right or vice-versa. Since the ultrasonic sensor alone does not provide directional information, the fusion of this information can be used to narrow the potential position of the tracked target. The combination of this sensor with an ultrasonic sensor is especially useful as humans are quite bad reflectors for sound waves. But with the additional information of the infrared sensor, this limitation can be overcome.

Other heat sources

Everything emitting radiation at the wavelength of about 8-14um will basically cause the sensor to fire. In an urban environment these are mainly other cars, respectively their motors. But for a side-looking system with the view mainly on the sidewalk, the main sources are pedestrians and cyclists.

III.3. Results

III.3.1. Ultrasonic sensor

Characteristics

Repeatability & Resolution

The resolution of the sonar system is limited by the width of a single pulse. As this pulse is very short (approximately 100µs), a resolution of better than 1.7cm can be achieved. More important than the resolution is the repeatability. The following tables shows measures of a plane surface at 1, 1.5, 2, 2.5 and 3meters, where each distance has been measured 100 times:

Table 3: Characteristics of the sonar system

Distance [m]	Standard Deviation [m]
1	0.0015
1.5	0.0081
2	0.0012
2.5	0.0102
3	0.0175

As foreseen, the resolution is in the order of magnitude of the 1.7cm.

Angle of view
The half angle of view has experimentally determined to be approximately 12°.

Range
The range is up to 5 meters for strong reflectors.

Tracking of multiple objects

This sensor system does not simply integrate the incoming signal until to a certain threshold is reached, as the conventional time-of-flight ultrasonic sensors do. This system can identify multiple objects (sources of echo). The following figure shows the return signal from 2 obstacles at 1.6 and 2.6meters.

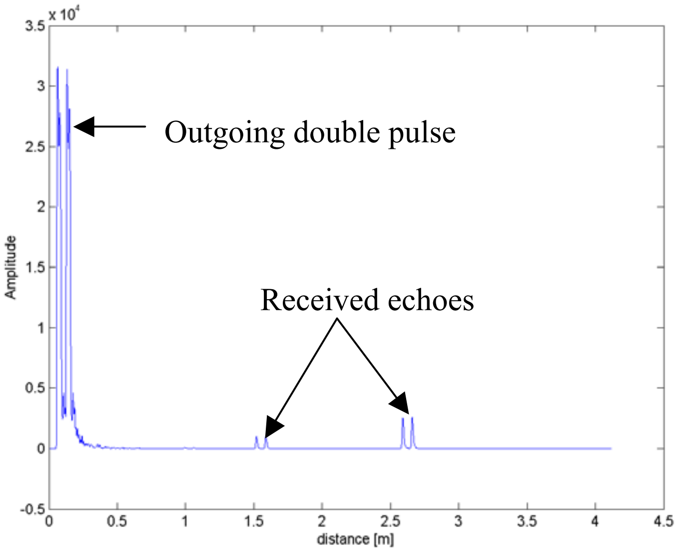

Figure 19: Return signal from 2 obstacles (at 1.5m and 2.6m). The difference in amplitude is due to the fact, that not every surface has the same reflective properties (and/or the same orientation towards the sensor).

The following figures demonstrate how close objects can lie next to each other without being perceived as only one object.
The sensor was mounted on a table for these experiments, and the obstacles where cartons, as can be seen in the figure below.

Figure 20: View on three carton obstacles in front of the sensor.

This configuration lead to following results.

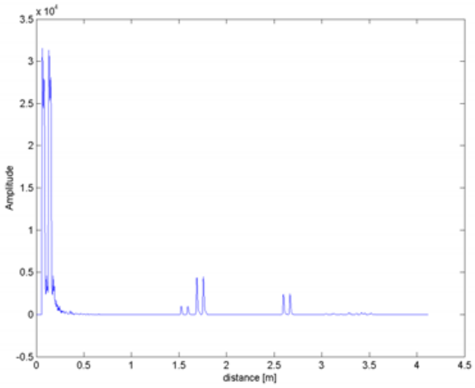

Figure 21: 3 objects at index 1.5m, 1.7m and 2.6m

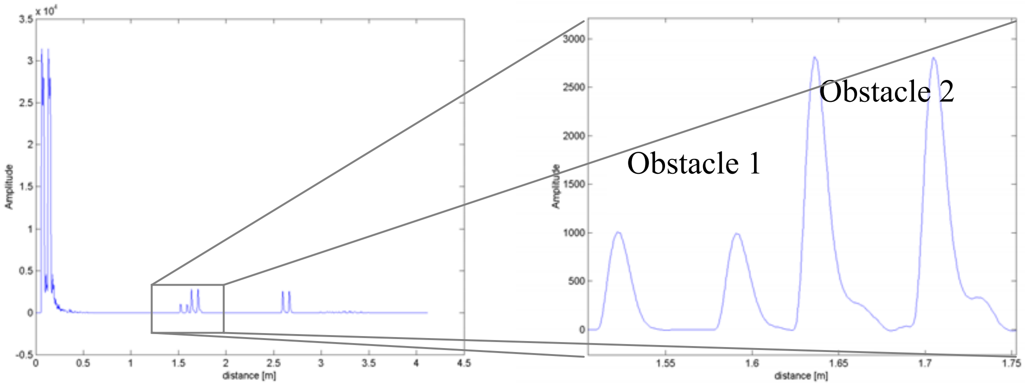

Figure 22: Objects are separated 11cm, the pulses are not overlapping, as can be seen in the magnification on the right hand side

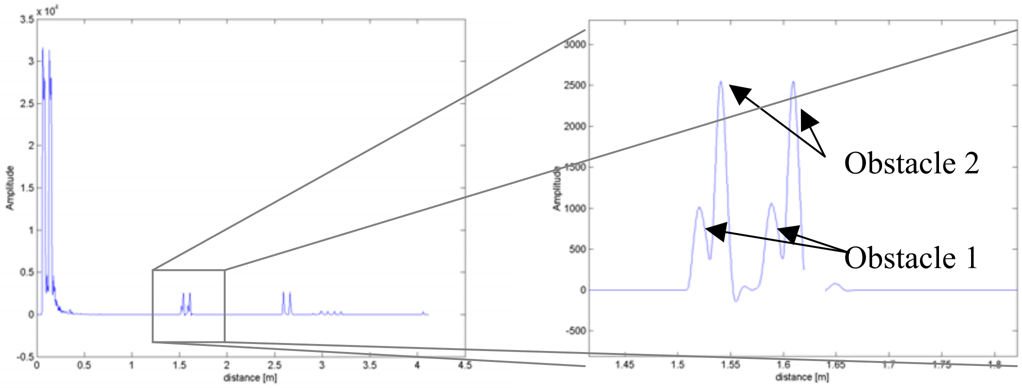

Figure 23: The objects are now separated by only 2cm, but the peaks are still distinguishable

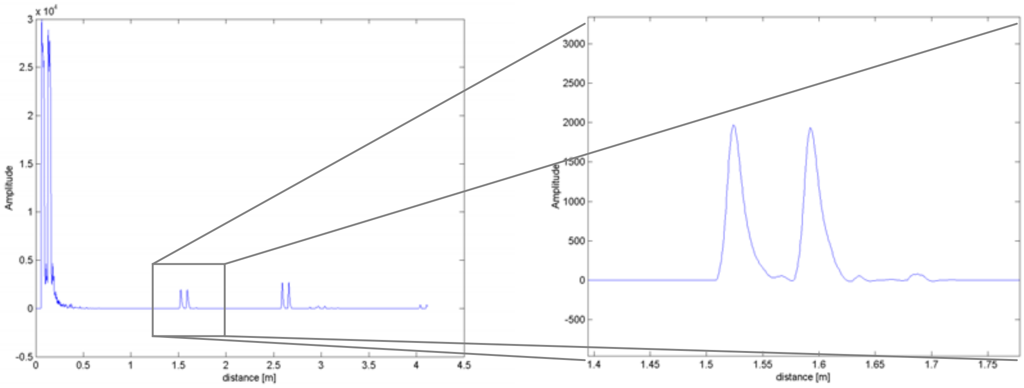

Figure 24:The peaks are no longer separated, therefore these two objects will be perceived as a single one.

For the application of short-range safeguarding the fact that objects closer than 2 cm can’t be discriminated, can be considered as sufficient.

III.3.2. Pyro-sensor

The range of the pyro-sensor is about 4 to 5 meters and allows normal speed for pedestrians. The half angle is approximately 15°. In order to test which speed of the heat source is allowed, the sensor has been mounted on the table (as for tests on the ultrasonic sensor, see above). The sensor has been mounted in order to discriminate between left-right or vice-versa movement.

Then a heat source has been moved at different speeds and in different distances to the sensor in front of the sensor.

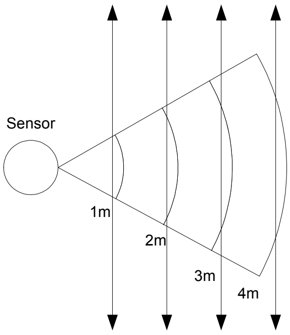

Figure 25: Test setup 1. The arrows indicate, where the test persons passed in front of the sensor

The first test was done letting a person walk slowly in front of the sensor. Detection occurred up to 5 meters. The second test was basically the same except that the person was running this time. No significant changes in comparison to the first test occurred.

In a second setup, it has been determined whether the sensor also detects heat sources heading directly to or from the sensor away.

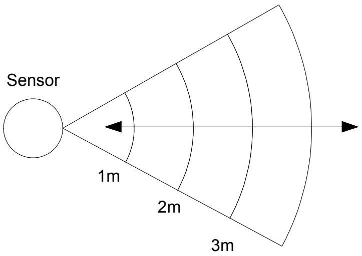

Figure 26: Test setup 2. The arrow indicates the direction, where the test person moved.

The third and fourth tests were the same as before just that the person walked towards the sensor. Even in this case as the left-right movement was very minimal, detection occurred in every case.

The sensor has also been tested outside, but apart from a short period, where it cooled down to ambient temperature and gave false results, it worked similar to the lab experiments.

IV. Distributed Sensing

This chapter gives a description of the algorithms used for the distributed sensing approach. It also shows that the combination of several sensors can exceed the sum of the single sensors, by applying smart algorithms. The novel "safety by the meter" approach is presented as a solution to hook up as many sensors as necessary without any changes in the networks software. The first paragraph will give an overview of the problems to be solved, followed by a paragraph of how these problems have been solved. At the end some results will be shown.

The low-level technological aspects of networks and protocols have been omitted in this work, as well as the situation where limited resources must be shared. The focus is on distributed sensing and the fusion of these information from multiple sensors. The algorithms have been implemented in a way to be as flexible as possible in order to allow any configuration of the network (linear array, planar array, completely arbitrary distribution in space of the modules). Also the number of sensors is not limited in any way. Anything from at least two to as many as necessary is supported, which permits the "safety by the meter" approach.

IV.1. General considerations and problems

When using multiple active sensors, such as ultrasonic transducers, one must first cope with sensor to sensor he interference. This has been explained in the previous chapter. Other issues are minimizing the dead zone, which is the area just in front of the sensor that cannot be covered because of double use of the transducer (during sending and some time afterwards, where the membrane is still oscillating, no signal can be received).

A similar problem is also that received signals might overlap, so a perfect reconstruction of all echoes is difficult. Though this can be handled by an adaptive firing schedule, which adapts each sensor's code and firing delay in order to minimize overlapping pulses and to increase the detection possibilities.

Using several sensors, the position of the target can be estimated with high precision (2 sensors give the bearing angle and range, whereas 3 sensors gives azimuth and elevation and range). Although a problem occurs, which is called the peak correspondence problem (see paragraph IV.3).

In order to allow for dynamic reconfiguration and plug and play (respectively plug and sense), a possibility for analyzing the sensor array at any time must be incorporated, finding the best possible "connections" between neighboring sensors.

As mentioned in chapter II, algorithms for basic classification have been studied before (using points, edges and surfaces for description)

Ideas on the topology of the sensor network are discussed after the above-mentioned issues.

IV.2. Adaptive firing schedule

As mentioned in the chapter before, no pulse compression is performed, which can lead to overlapping pulses, which are hard to distinguish or to detect, as the confidence level for the amplitude is no longer useful (pulses are said to belong together whenever their amplitudes are very similar): Depending on the phase of two overlapping pulses, interference can occur, so that the overlapped pulse can actually be as strong as the sum or as weak as the difference between the two amplitudes.

But it can be detected, that there are code matches sharing one peak together (and having a low amplitude confidence level), who are likely to be overlapping pulses. In this case, the system will adapt the firing sequence so the pulses are clearly separated leading to best results. In general the nearest target having overlapping peaks will be used for the new firing schedule, taking into account the code changes for the next measurement cycle. The following figures with real data demonstrate the adaptive firing schedule. The echo can be seen at around 1.4m.

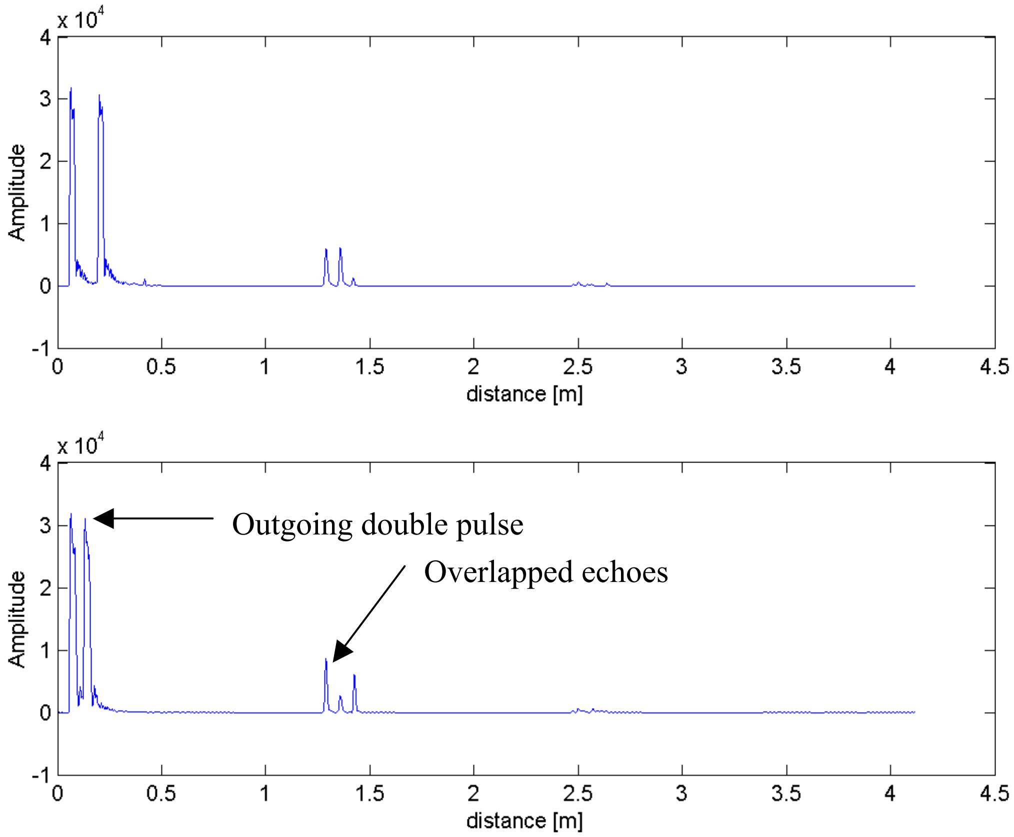

Figure 27: The signals of two sensors fired at the same time. Sensor 1 (above) has a pulse separation of 800us and sensor 2 (below) a separation of 400us.

In the picture above it can be seen that the two sensors are fired at the same time. There is a target about 1.4m away and as the inter-sensor spacing is very small (10cm), the two pulses are overlapping. As one can easily see, the amplitudes do no longer correspond to the amplitude confidence and it is difficult, without other knowledge to separate the pulses.
Although a match with low amplitude confidence can be detected and the firing schedule will be adapted for he next cycle in order to separate the overlapping pulses (see next figure).

Two implementations were tested: The first one assigned a random delay to one of the sensors and the second one used the time between the pulses from one other as the delay of the other.

In case the active range limitation were active (codes change from one measurement cycle to the other), the latter implementation used the code for the next cycle.

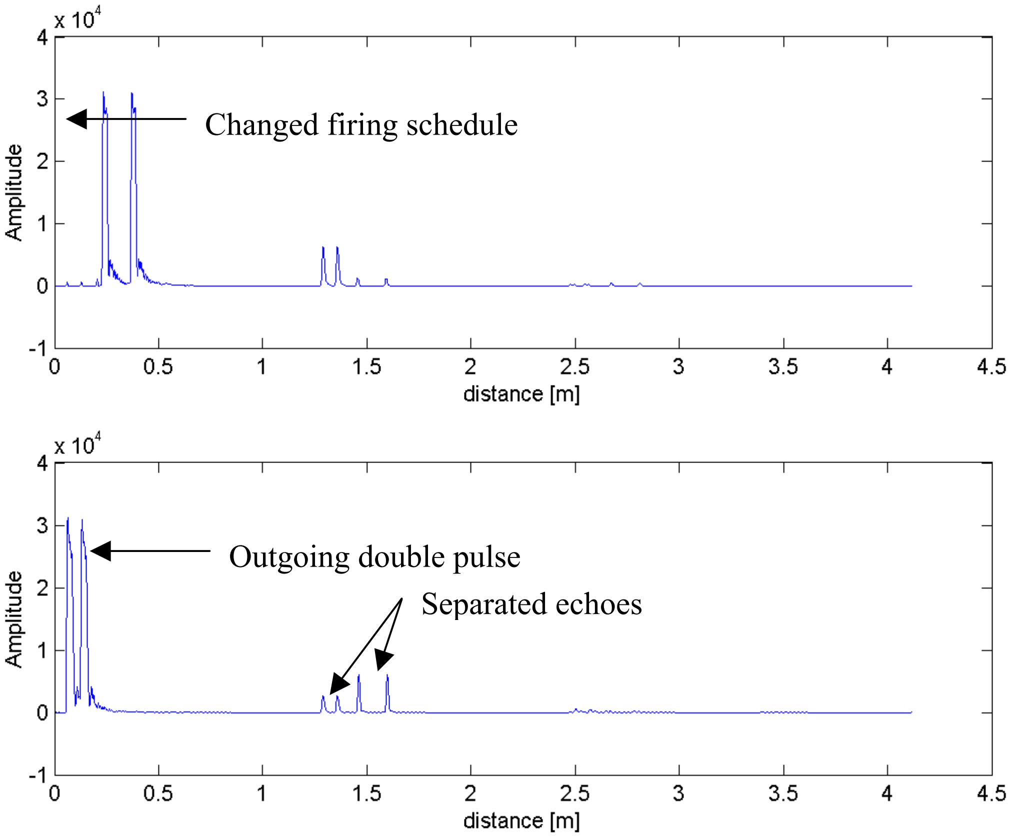

Figure 28:After schedule adaptation, the pulses are clearly separated and can be processed with more confidence in its results. The codes have not been changed in this example. Note that the firing delay of sensor 2 (below) is different to sensor 1 (above) and that the amplitudes of corresponding peaks are very similar.

IV.3. Peak correspondence problem

When many sensors are simultaneously emitting and triangulation for precise 2D or 3D localization of more than one target shall be performed, the problem of finding the corresponding echo in each sensor's signal arises. If these correspondences are perfectly resolved, the system can calculate the angles to the object. But the following figures show that this is not always the case:

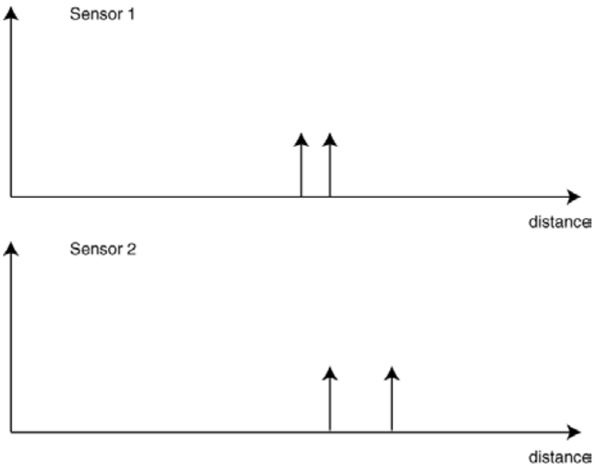

Figure 29: The extracted matches from two sensor's signals. Sensor 1 sees two objects relatively together, whereas sensor 2 sees the same objects farther away. (The arrows designate a matched code and not individual pulses)

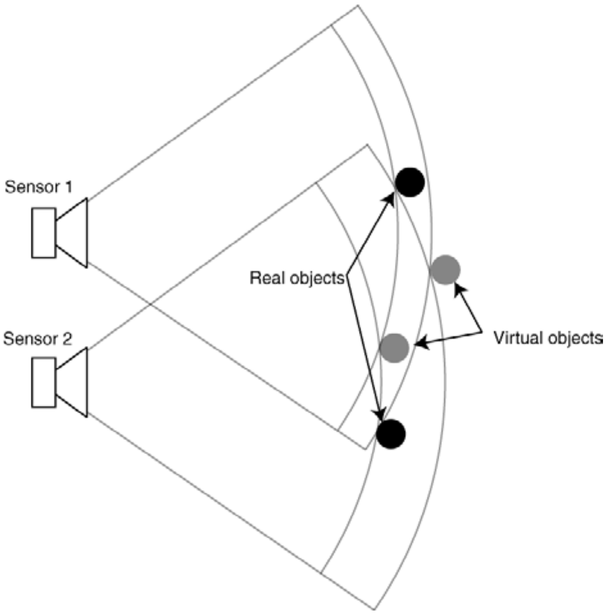

Figure 30: The correspondence problem leads to 4 possible objects (2 real and 2 virtual objects)

In this example, both sensors see two objects, at two distinct distances. As it is not known a priori which peak in one sensor's signal corresponds to which peak in the other's sensor signal, there are actually 4 possible objects, which can be seen as two real objects and two virtual objects.

Using a small baseline decreases this problem, as in this case the nearest object for one sensor is very likely also the nearest for the other sensor.

But in order to be not limited to short baselines, the cross-talk information can be taken into account: As each sensor delivers n results for n objects, we have theoretically n^m (with m sensors) possible objects, where only n of them are real. But if the cross talk is considered (distance between one sensor via an object to another sensor), this gives $n^{(m-1)}$ another datasets, so we can again extract exactly n objects.

This can be seen (for example 2 sensors and 2 objects) in geometrical terms as the intersections of 4 circles, giving 4 possible points. But if the distance from sensor 1 via object 1 to sensor2 is known, we can spawn an ellipse with focal point centered in the sensors position, on which only one of the 4 points is lying. Doing the same with the inter-distance of the other object, 2 points can be eliminated and the two real objects are found (see figure below).

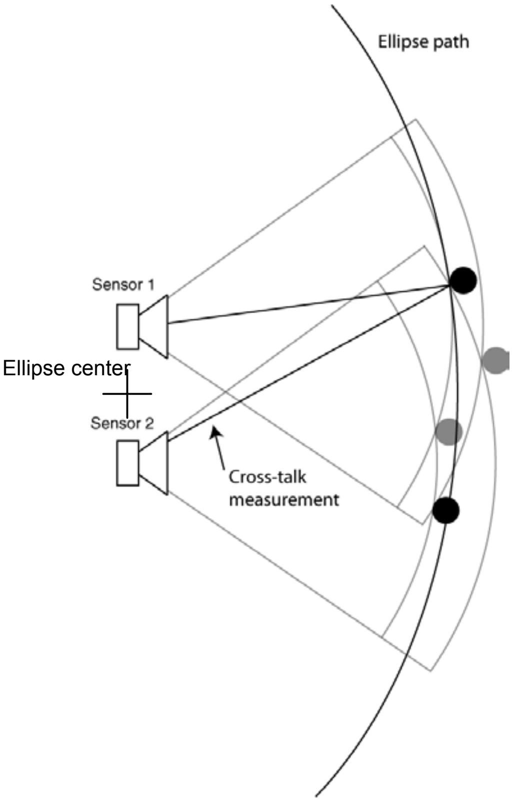

Figure 31: Resolved correspondence problem. The ellipse's path spawn by the cross-talk distance for the first object (top) does automatically exclude one virtual object. The same is true for when using the crosstalk for the second object, so that only the real objects will stay.

IV.4. Dead zone minimization

During the emitting sequence (200 to 1000us) and a short time afterwards (approximately 200us), no signal can be received, leading to a dead zone in front of the sensor (see Figure 9).

This dead zone corresponds therefore to 7 to 20 centimeters, depending on the pulse separation. When the sensors are all firing at the same time, there will be an uncovered area in front of all sensors, but if the firing schedule lets them fire at different times, the dead zone will actually be moving from the front of one sensor to the other, letting only the front of one sensor uncovered at a time.

Of course this is only true when the sensors are relatively close to each other, so that a sensor next the firing one can receive an eventual reflection of a near target.

IV.5. Topology

The algorithms have been designed to be as open as possible, no restrictions on the topology is included. Although the designer of the safety system must base his choice weighting following conditions:

- Geometry of the sensor's field of view
- Needed coverage
- Objects to be sensed
- Maximum cost of the system

The first two points take into account the angle of view of a single sensor and the size of the vehicle. The coverage in this context is not equivalent to the range of the sensors, but is defined as the area, or volume the whole system must be able to cover.

The minimum coverage defines the spacing between the sensors, which is where the fields of view of the individual sensors overlap and depends only on the opening angle of the sensor.

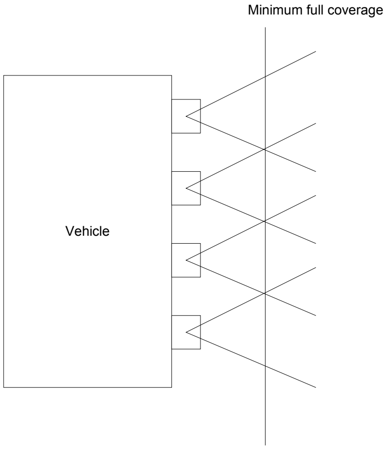

Figure 32: The minimum full coverage is given, where the field of view of the individual sensors overlap

The smaller the baseline, the better the coverage, but the amount of sensors used to cover the whole car increases ("safety by the meter").

The third point should answer which direction of movement of a heat source the pyro-sensor shall basically detect. In the vehicle safety application, a detection of moving heat-sources parallel to the ground seems to be the main solution in most cases.

If higher bearing resolution is desired for the ultrasonic sensors, their baseline must be small, in order at least 2 sensors detect the same object.

The last conditions must also take into account the integration cost of the sensor system, as in addition to the purely hardware related costs, the cost for the wiring and assembly must be included.

IV.6. Array analysis & reconfiguration

In order to permit an easy setup without changing anything in the software, any kind of array structure such as linear or two-dimensional array is supported. The system analyzes the

positions of all sensors and determines whether the sensors form a linear or 2D array (a 3D array could also be implemented, but is not very useful).
In a second step, the positioning of the individual sensors define together with the field of view, which sensors can actually profit from each other (e.g. use triangulation for better bearing resolution):
These are in general those who have a small baseline between them (see figure below).

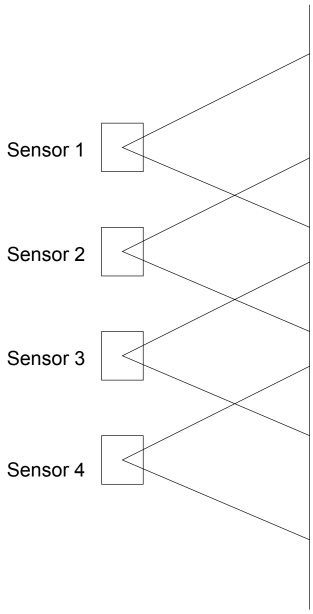

Figure 33:In this example, Sensor 2 only searches for signals of sensor 1 and 3 in its received signal, as it does not receive a signal from sensor 4

In order to allow dynamic reconfiguration, this analysis has to be performed repeatedly, in order to detect a missing or added sensor module. The only condition for adding a sensor completely automatically to the system is that the added sensor knows its position, which can be broadcasted to the rest of the network.

IV.7. Network Connections

In order to make above-mentioned algorithms possible, the following information must be passed between the nodes of the network:

- Each module broadcasts its ultrasonic code to the other sensors.
- Each module broadcasts its ultrasonic firing schedule to the other sensors.
- Each module broadcasts the state of the pyro-electric sensor to the other sensors.

Actually, if the array analysis (see above) is used, this information has only to be transmitted to the neighbors, which decreases the amount of information that has to be passed over the network.

V. Applications

An idea of all the possible applications and especially for the Navlab application will be described in this chapter.

V.1. Experimental setup:

In order to save time during the development but still be possible to demonstrate the distributed sensing networks capabilities, no embedded computers or processors have been used. A common Personal Computer (Pentium II) under Windows 2000 professional operating system with a rapid data acquisition board has been used instead of single modules. Although the code (entirely written in C/C++) has been designed to be easily ported to any other platform. Only the low-level data acquisition and signal generation routines and the high-level visualization routines have to be adapted.

Two experiments have been conducted. The first one, using only two sensors detects the curb on the side, which, as mentioned before can be very useful to discriminate objects (and particularly pedestrians) into objects in danger (off curb) and most likely not endangered (on curb). This demonstrates the basic teamwork between sensors.

The other experiment, involving more sensors demonstrates far more the networking part of this project. Also it incorporates the use of the person detection sensors and the sensor fusion.

V.2. Curb detection

Curb detection is not only useful for determining which pedestrians are possibly in danger. It is also useful for buses to “dock” onto the sidewalk, so it is easier for people to get in and out (especially for handicapped people). It could also be used (together with sensors in front and back) to simply park a vehicle on the curb.

V.2.1. Configuration

Several reasons influenced the choice on how the sensors have been mounted:

- In order to prevent scattering, the sound wave should hit the curb ideally at a perpendicular angle. This can be achieved by mounting the sensors as near to the ground as possible.
- A minimum distance to the ground must be respected
- A short baseline is desirable in order to eliminate the peak correspondence problem (see IV.3) and to minimize the used space.

The sensors have finally been mounted in the middle of the front bumper, slightly inclined. This configuration allows a detection of the curb from 0m (tot the car’s side) to up to 3m.

The following picture shows the configuration mounted on Navlab11:

Figure 34: The curb detection setup. Two sensors are mounted next to the front bumper (in the center of the white circle)

This configuration uses several of the algorithms described in chapter III and IV:

- Every sensor has its own code, which changes from one measurement cycle to the next
- The active range limitation is implemented in order to increase the frame-rate and in order to prevent echoes from multiple reflections
- Only the 2D information (both sensors must detect its own and the other sensor's echo) is used in order to increase the confidence of the measured signal.
- The adaptive firing schedule is active, although changes are very rare

The information from the pyro-sensor is not used in this special application.

V.2.2. Results

The information gathered by the this system has been overlaid onto the images from the right side looking camera in order to allow easy visualization of the results.

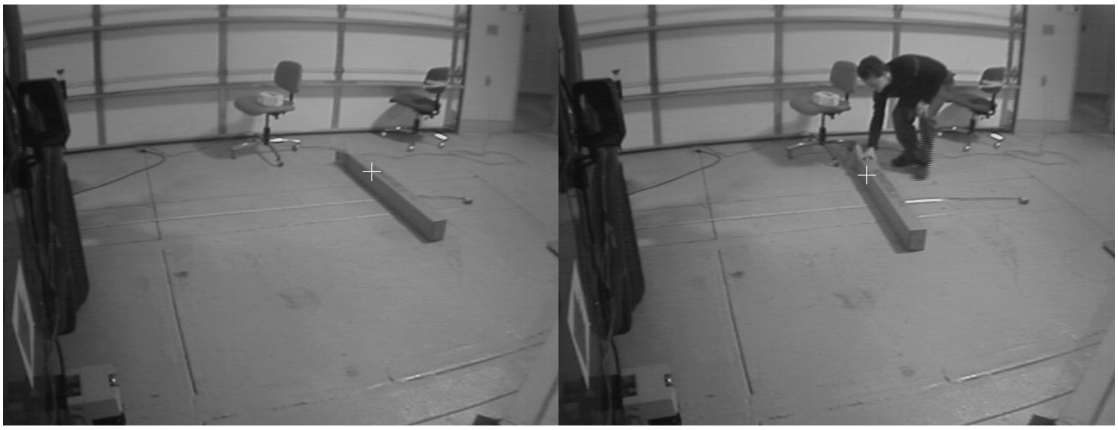

Figure 35: Detection of the curb in the lab at several distances. The white cross designates where the system sees the curb.

Figure 36: Detection of the curb on the CMU campus. On the top right image, detection failed

The sonar information has been processed in a very conservative manner: The amplitude of each double pulses pulse must be very similar and both sensors must detect the obstacle and the cross talk of the other sensor.

This rejects false readings very efficiently, but leads to missing information during some measurement cycles (see Figure 36 top-right image).

V.3. Side-looking pedestrian detector

As many accidents on buses happen on the side, a sensor configuration covering the side of the vehicle is simulated.

V.3.1. Configuration

Two configurations for this application were initially studied:

- An array of sensors at low height, looking parallel to the ground
- An array of sensors looking down at the side of the vehicle from the roof

The first solution has been implemented because of following reasons:

- Bigger area covered
- Mounting them on the side-strip bumper is more logical in terms of assembly on real vehicles

The system was tested in the lab: A test person walked across different directions, ranges and speeds in front of the array.

The figure below shows Navlab11 with 4 sensors mounted on its right side.

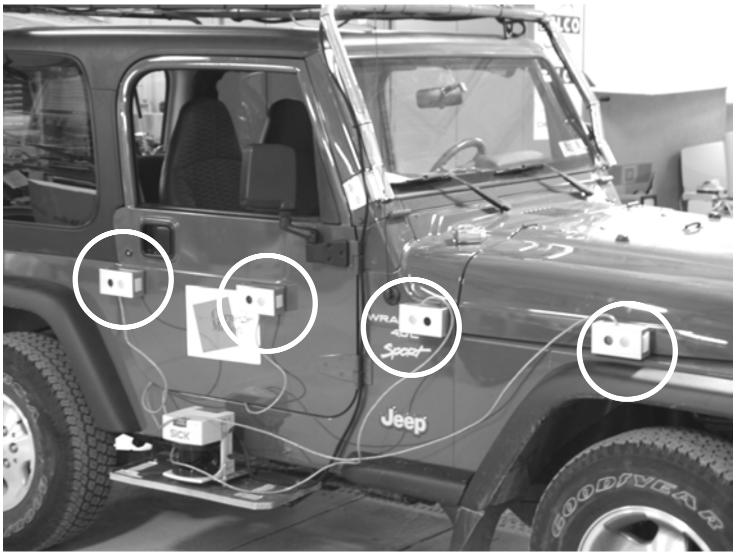

Figure 37: Navlab11 with 4 side looking sensor modules looking parallel to the ground

The spacing between the sensors in this test is quite large (50cm), so no triangulation can be done for close targets but much less sensors are needed to cover a large part of the vehicle.

V.3.2. Results

The ultrasonic sensors don’t detect pedestrians very well. Humans are very bad reflector compared to a flat and hard surface or a sharp corner and it is almost impossible to detect a human at more than 2 meters.
This fact and the large baseline leads to a sensor network where no triangulation is done, and therefore only range information exist. Although the test person was not undetected because of the pyro-sensor. The combination allows detecting persons up to 4 meters, ultrasonic range

data are only available for targets closer than 2 meters. The figure below shows a sequence of the test person walking across the vehicle’s side.

Pyro-sensor 1 detects a movement from the front of the car to the rear

Pyro-sensor 1 still detects a movement
Pyro-sensor 2 starts to detect a front-rear movement

Pyro-sensor 1 and 2 don’t detect anymore
Pyro-sensor 3 detects the same movement
Ultrasonic sensor 3 detects an object

Figure 38:Sequence of a person moving in front of the wide baseline array (left .The sensors are numerated from 1 (front) to 4 (rear)

In the sequence above (from top left to bottom right) the pyro-sensor of each module detects a person moving from the front of the car to the rear, but the range measurements were only successful on the last image.

Good detection of humans with the ultrasonic sensors was achieved when the person was only one meter away from the vehicle. If people have to be tracked when falling under the bus, this would be a sufficient distance, as people further away are assumed to be in security.

VI. Conclusion.

The built system presents only a prototype, and a lot more could still be done. The system can be made much smaller and lighter. At the same time, an onboard logic and processor should be integrated. This allows exploring the issues of networking in terms of the hardware (wiring) and software (protocols). On top of this architectural issue, the dynamic reconfiguration and organization of the network would be especially interesting to explore.

If the sensor's development toward an automotive sensor is pursued, the following considerations must be taken into account:

- Integration with the other sensors of the vehicle provides additional information, such as the vehicle's ego-motion (which could be used to turn the ultrasonic sensors off, when a certain speed is exceeded)
- Integrating the sensor modules into a real vehicle poses the problem on how the sensors should be wired and how (and where) they should be mounted on the car

Other application might also profit from this sensor system like indoor mobile robots (especially as this the environment is a less dynamic one).

Here, a low-cost sensor system was proposed and built, and distributed sensing successfully demonstrated. The ultrasonic sensor showed some weaknesses in terms of detecting humans at longer range or when used at higher speed. However the pyro-sensor has proven to be a very sensitive device, making it easy to detect the presence of a pedestrian, but without any information about his position or distance to the vehicle. The low-speed scenarios where this system is suitable are:

- Accelerating / braking near crosswalks, traffic lights, intersections.
- Busses at bus stops.

But accidents happen at these locations and if any of them can be prevented, the use of this system should be considered.

For other applications, especially at higher speed, the replacement of the ultrasonic sensor is necessary. The combination of the pyro-sensor with another sensor modality could be very interesting.

Pittsburgh, 21-02-03

Christian Wengert

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Appendix I. Electronic circuits

I.1 Ultrasonic Sensors

Driver electronic

The driver electronics uses only simple standard discrete electronics and can Therefore bne implemented very cheaply. The 400 volt peak-to-peak voltage for the transducer is generated by two transistors and a small transformer in a fly-back mode. The bias-voltage of 200V is provided by two Zener diodes.

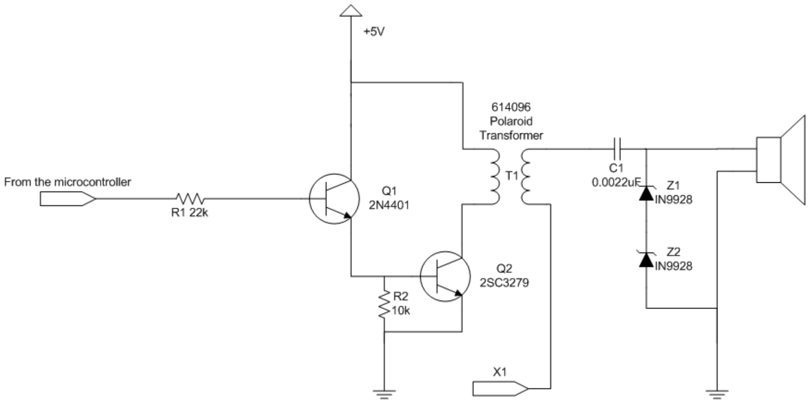


Figure 39: Ultrasonic transducer driver electronics

The return signal is amplified and filtered by a one stage operational amplifier circuit (which basically serves to prevent aliasing of the signal when sampled).

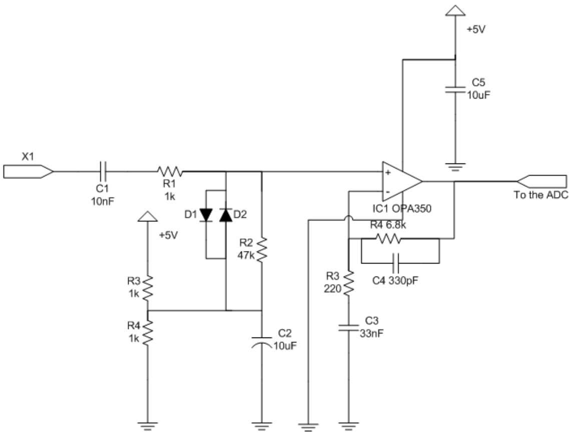


Figure 40: Amplifier and filter circuit for the Polaroid transducer

I.2 Pyro-electric device

Electronics

A two stage amplifier circuit with a total gain of 5000 feeds the signal of the pyro-electric device into a window comparator. The direction of the target is given by a high signal from the first comparator output following by a high signal from the other comparator (and vice-versa). The signal is also low-pass filtered at about 10Hz in order to reject high frequency noise from the environment.

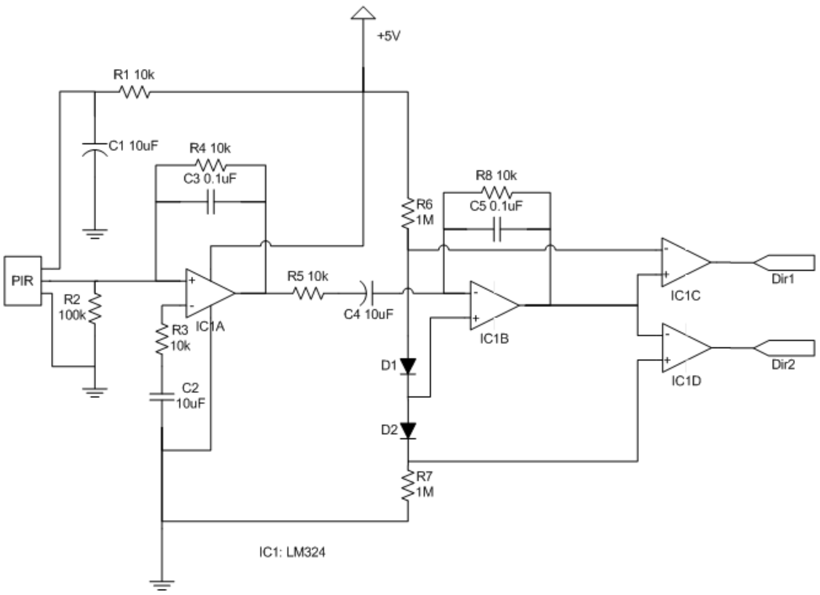


Figure 41: Amplifier and window comparator circuit for the pyro-sensor

In order to accept a wider range of input voltages, a standard voltage regulator is incorporated.

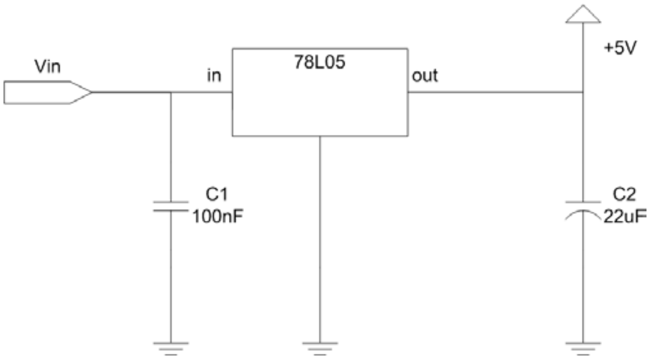


Figure 42:Voltage regulator

I.3 Shielding

It has been seen, that the pulse generation, which corresponds to a two ampere peak during 100us induces a lot of noise. Also the transducer itself and especially its cable to the electronics were serving as antennas for all sort of noise (already in the lab environment). In order to get best results, the sensors PCB has a ground-plane and is mounted in a grounded metal case. Also all outgoing cables are shielded coaxial cables.

Appendix II. Datasheets

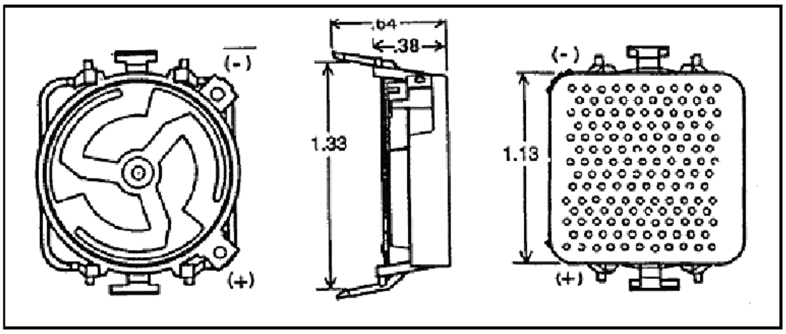
II.1Polaroid 7000 Series transducer

Figure 43: The Polaroid 7000 Series electrostatic transducer

Technical Specifications for

7000 Series **Electrostatic Transducers**

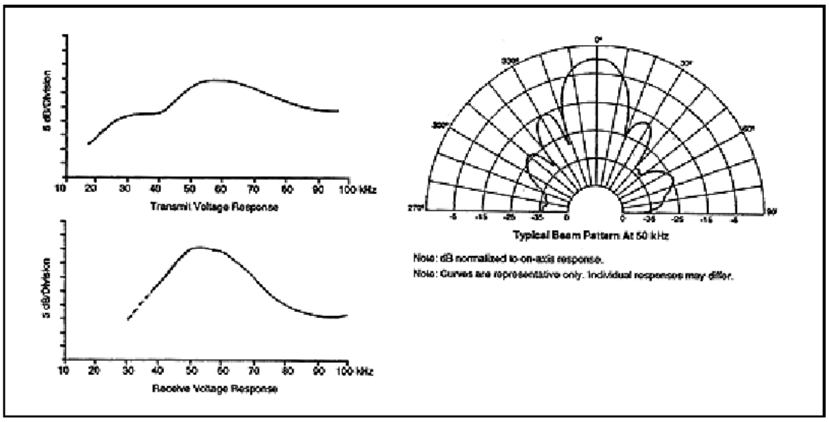
Part#616736-Minimum order 10. Increments of 10…Part #612366-Minimum order 100, increments of 100



Specifications

Usable Transmitting Frequency Range	See Graph	Maximum Combined Voltage	400V
Usable Receiving Frequency Range	See Graph	Capacitance at 1 kHz (Typical)	600-700 pf
Beam Pattern	See Graph	150 vdc bias	
Minimum Receiving Sensitivity at 50 kHz	106.9 dB	Operating Conditions	
300 vac pk-pk, 150 vdc bias		Temperature	32°-1140°F
(dB re 20µPa at 1 meter)		Relative Humidity	5%-95%
Minimum Receiving Sensitivity at 50 kHz	-43.4dB	Standard Finish	
150 vdc bias (dB re lv/Pa)		Foil	Gold
		Housing	Black
Suggested DC Bias Voltage	200V		
Suggested AC Driving Voltage (peak)	200V		

Specifications subject to change without notice.



Note: dB normalized to on-axis response.
Note: Curves are representative only. Individual responses may differ.

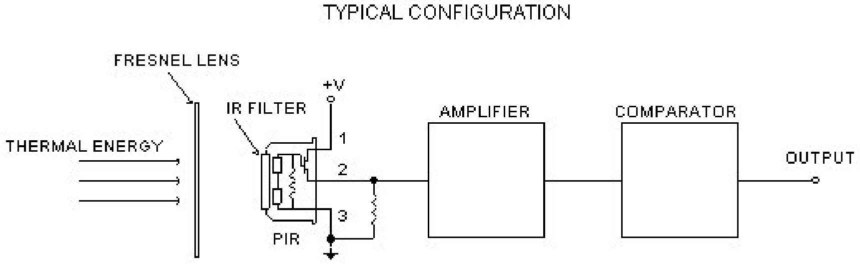
Comparison Chart

System Specifications	**Instrument Grade Part #604142/616341**	***Environmental Grade Part #607281/616342**	**7000 Series Part #612366/616736**
Distance Range	0.15 to 10.7m (0.5 to 35ft.)	same	same
Resolution ±1% over entire range	±3mm to 3m (± 12 to 10ft.)	same	same
Operating Conditions			
• Temperature	-30° to 70°C (-20° to 160°F)	same	0° -60°C (32° -140°F)
• Relative Humidity	5% to 95%	same	same
Beam Angle Typical, at 3dB down	12°	12°	17°
Transducer Drive Signal			
• Gated Sine Wave	50 kHz	same	same
• Duration	1.1 ms	same	same
• Suggested AC Drive Voltage	150v	same	200 V
• Bias Level	150 vdc	same	200 V
• Max. Combined Voltage	400v	same	same
Min. Transmitting Sensitivity at 50 kHz	110dB	same	106.9dB
• 300 vac pk-pk, 150 vdc bias			
• (dB re 20µPa at 1 meter)			
Min. Receiving Sensitivity at 50 kHz	-42dB	same	-43.4dB
• 50 kHz, 150 vdc bias(dB relv/Pa)			
Capacitance at 1 kHz (typical)	380-410 pf	same	650 pf
Power Requirements Ranging Module			
• Voltage	6 vdc (4.5 – 6.8 vdc)	same	same
• Current	2.0 amps (1ms pulse)	same	same
	100 ma quiescent	same	same
Standard Finish			
• Foil	gold	same	same
• Housing	Flat black cold roll steel	304 stainless steel	Flat black plastic
Weight			
• Transducers	8.2 gm (0.29oz)	same	4.6 gm (0.150 oz)
• Modules	18.4 gm (0.94oz)	same	same
Dimensions			
• Thickness • Diameter	0.46 in. 1.69 in.	same same	0.41 in. 1.13 in. sq.

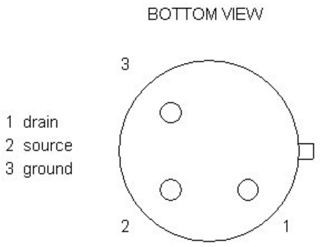
II.2Pyro-electric sensor

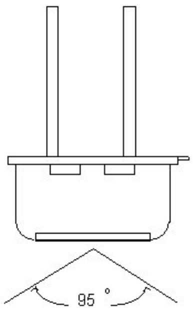
The pyro-electric sensor is made of a crystalline material that generates a surface electric charge when exposed to heat in the form of infrared radiation. When the amount of radiation striking the crystal changes, the amount of charge also changes and can then be measured with a sensitive FET device built into the sensor. The sensor elements are sensitive to radiation over a wide range so a filter window is added to the TO5 package to limit incoming radiation to the 8 to 14mm range which is most sensitive to human body radiation.

Typically, the FET source terminal pin 2 connects through a pull-down resistor of about 100 K to ground and feeds into a two stage amplifier having signal conditioning circuits. The amplifier is typically bandwidth limited to below 10Hz to reject high frequency noise and is followed by a window comparator that responds to both the positive and negative transitions of the sensor output signal. A well filtered power source of from 3 to 15 volts should be connected to the FET drain terminal pin 1.



The PIR325 sensor has two sensing elements connected in a voltage bucking configuration. This arrangement cancels signals caused by vibration, temperature changes and sunlight. A body passing in front of the sensor will activate first one and then the other element whereas other sources will affect both elements simultaneously and be cancelled. The radiation source must pass across the sensor in a horizontal direction when sensor pins 1 and 2 are on a horizontal plane so that the elements are sequentially exposed to the IR source.



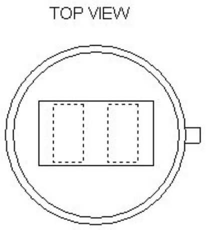


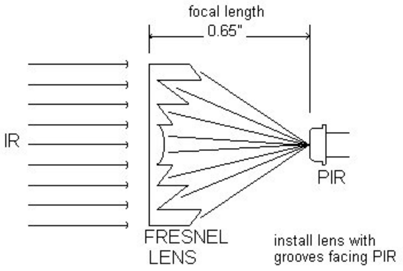
View Angle

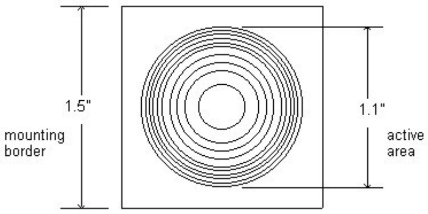
PIR325

SENSITIVE AREA 2 ELEMENTS
SPECTRAL RESPONSE 5 - 14 um
OUTPUT VOLTAGE mv pp 20
NOISE uVpp 20
OFFSET VOLTAGE volts 1.0
SUPPLY VOLTAGE volts 2.5 - 15
OPERATING TEMP c 30 - 70

Test Conditions for output voltage:
Supply voltage = 5 volts
100K load resistor from pin 2 to 3
IR source = Hand moving 6" from sensor



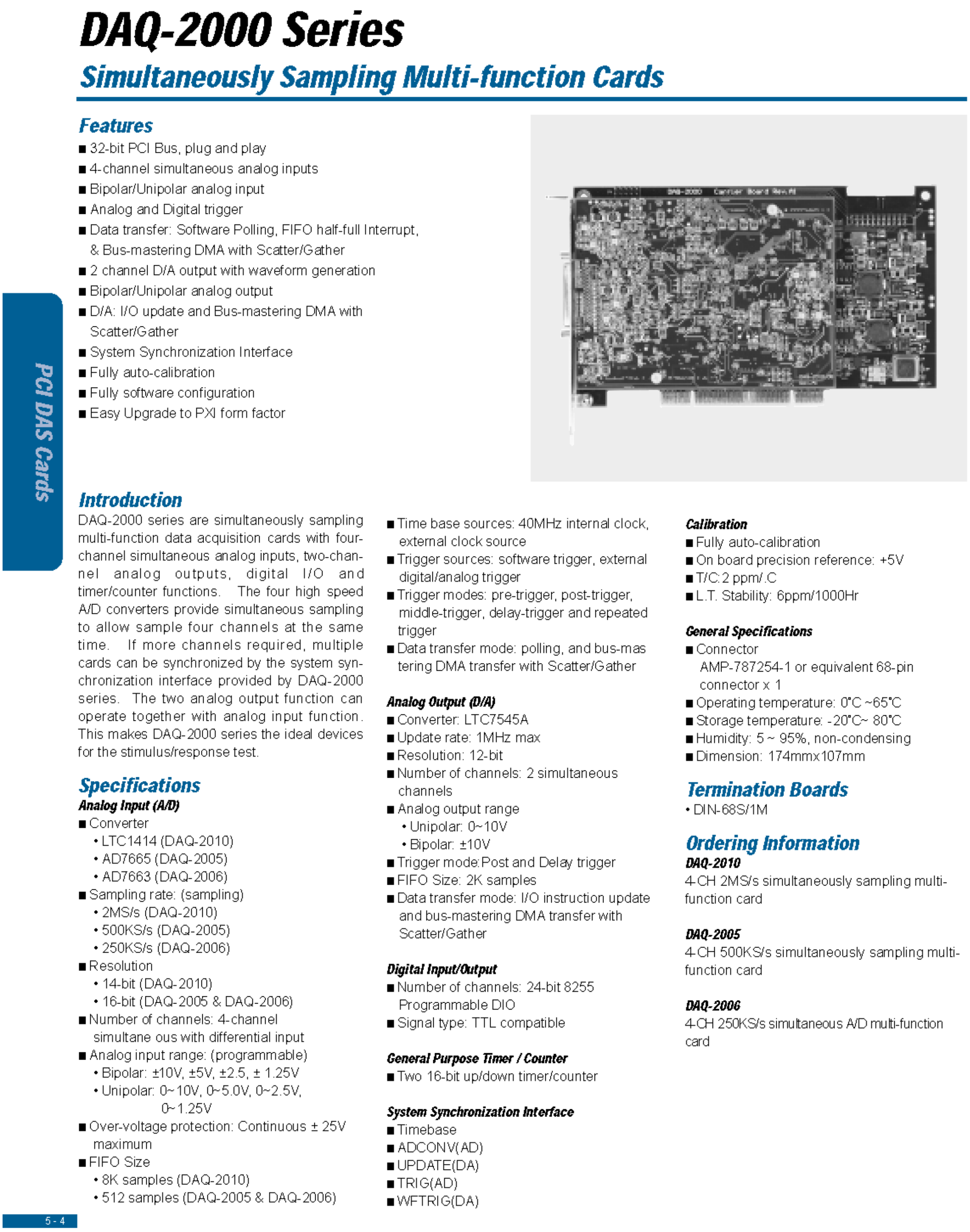




0.015" thickness

Optimum transmittance in the 8 to 14 um region

II.3 DAQ-2005 Data acquisition board



DAQ-2000 Series

Simultaneously Sampling Multi-function Cards

PCI DAS Cards

Features

- 32-bit PCI Bus, plug and play
- 4-channel simultaneous analog inputs
- Bipolar/Unipolar analog input
- Analog and Digital trigger
- Data transfer: Software Polling, FIFO half-full Interrupt, & Bus-mastering DMA with Scatter/Gather
- 2 channel D/A output with waveform generation
- Bipolar/Unipolar analog output
- D/A: I/O update and Bus-mastering DMA with Scatter/Gather
- System Synchronization Interface
- Fully auto-calibration
- Fully software configuration
- Easy Upgrade to PXI form factor

Introduction

DAQ-2000 series are simultaneously sampling multi-function data acquisition cards with four-channel simultaneous analog inputs, two-channel analog outputs, digital I/O and timer/counter functions. The four high speed A/D converters provide simultaneous sampling to allow sample four channels at the same time. If more channels required, multiple cards can be synchronized by the system synchronization interface provided by DAQ-2000 series. The two analog output function can operate together with analog input function. This makes DAQ-2000 series the ideal devices for the stimulus/response test.

Specifications

Analog Input (A/D)

- Converter
  - LTC1414 (DAQ-2010)
  - AD7665 (DAQ-2005)
  - AD7663 (DAQ-2006)
- Sampling rate: (sampling)
  - 2MS/s (DAQ-2010)
  - 500KS/s (DAQ-2005)
  - 250KS/s (DAQ-2006)
- Resolution
  - 14-bit (DAQ-2010)
  - 16-bit (DAQ-2005 & DAQ-2006)
- Number of channels: 4-channel simultane ous with differential input
- Analog input range: (programmable)
  - Bipolar: ±10V, ±5V, ±2.5, ± 1.25V
  - Unipolar: 0~10V, 0~5.0V, 0~2.5V, 0~1.25V
- Over-voltage protection: Continuous ± 25V maximum
- FIFO Size
  - 8K samples (DAQ-2010)
  - 512 samples (DAQ-2005 & DAQ-2006)
- Time base sources: 40MHz internal clock, external clock source
- Trigger sources: software trigger, external digital/analog trigger
- Trigger modes: pre-trigger, post-trigger, middle-trigger, delay-trigger and repeated trigger
- Data transfer mode: polling, and bus-mastering DMA transfer with Scatter/Gather

Analog Output (D/A)

- Converter: LTC7545A
- Update rate: 1MHz max
- Resolution: 12-bit
- Number of channels: 2 simultaneous channels
- Analog output range
  - Unipolar: 0~10V
  - Bipolar: ±10V
- Trigger mode:Post and Delay trigger
- FIFO Size: 2K samples
- Data transfer mode: I/O instruction update and bus-mastering DMA transfer with Scatter/Gather

Digital Input/Output

- Number of channels: 24-bit 8255 Programmable DIO
- Signal type: TTL compatible

General Purpose Timer / Counter

- Two 16-bit up/down timer/counter

System Synchronization Interface

- Timebase
- ADCONV(AD)
- UPDATE(DA)
- TRIG(AD)
- WFTRIG(DA)

Calibration

- Fully auto-calibration
- On board precision reference: +5V
- T/C:2 ppm/.C
- L.T. Stability: 6ppm/1000Hr

General Specifications

- Connector
  AMP-787254-1 or equivalent 68-pin connector x 1
- Operating temperature: 0˚C ~65˚C
- Storage temperature: -20˚C~ 80˚C
- Humidity: 5 ~ 95%, non-condensing
- Dimension: 174mmx107mm

Termination Boards

- DIN-68S/1M

Ordering Information

DAQ-2010

4-CH 2MS/s simultaneously sampling multi-function card

DAQ-2005

4-CH 500KS/s simultaneously sampling multi-function card

DAQ-2006

4-CH 250KS/s simultaneous A/D multi-function card

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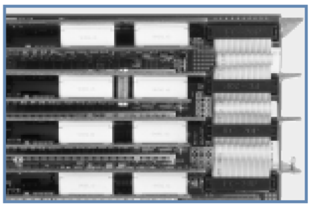
Pin Assignment table

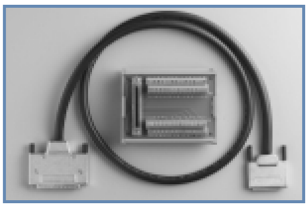
Pin#	Signal Name	Reference	Direction	Description
1~4	CH<0..3>+	CH0<0..3>-	Input	Differential positive for AI channel <0..3>
5	EXTATRIG	AIGND	Input	External AI analog trigger
6	DA0OUT	AOGND	Output	AO channel 0
7	DA1OUT	AOGND	Output	AO channel 1
8	AOEXTREF	AOGND	Input	External reference for AO channels
9~12	SDI<3..0>_1 (2010) NC (2005/2006)	DGND	Input	Synchronous digital inputs
13	AO_TRIG_OUT	DGND	Output	AO trigger signal
14	AI_TRIG_OUT	DGND	Output	AI trigger signal
15,16	GPTC<0,1>_SRC	DGND	Input	Source of GPTC<0,1>
17,51	GPTC<0,1>_GATE	DGND	Input	Gate of GPTC<0,1>
18,52	GPTC<0,1>_OUT	DGND	Input	Output of GPTC<0,1>
19,53	GPTC<0,1>_UPDOWN	DGND	Input	Up/Down of GPTC<0,1>
20	EXTTIMEBASE	DGND	Input	External TIMEBASE
21,28,49, 50,54,62	DGND	–	–	Digital ground
22,56,23, 57,24,58, 25,59	PB<7,0>	DGND	PIO*	Programmable DIO pins of 8255 Port B
26,60,27, 61,29,63, 30,64	PC<7,0>	DGND	PIO*	Programmable DIO pins of 8255 Port C
31,65,32, 66,33,67, 34,68	PA<7,0>	DGND	PIO*	Programmable DIO pins of 8255 Port A
35~38	CH<0..3>-	–	Input	Differential negative input for AI channel <0..3>
39	AIGND	–	–	Analog ground for AI
40~42	AOGND	–	–	Analog ground for AO
43~46	SDI<3..0>_0 (2010) NC (2005/2006)	DGND	Input	Synchronous digital inputs
47	EXTWFTRIG	DGND	Input	External AO waveform trigger
48	EXTDTRIG	DGND	Input	External AI digital trigger
21	AFI1	DGND	Input	Auxiliary Function Input 1 (ADCONV, AD_START)
55	AFI0	DGND	Input	Auxiliary Function Input 0 (DAWR, DA_START)

68-pin Connector Pin Assignment

CH0+	1	35	CH0-
CH1+	2	36	CH1-
CH2+	3	37	CH2-
CH3+	4	38	CH3-
EXTATRIG	5	39	AIGND
DA1OUT	6	40	AOGND
DA0OUT	7	41	AOGND
AOEXTREF	8	42	AOGND
SDI3_1/NC*	9	43	SDI3_0/NC*
SDI2_1/NC*	10	44	SDI2_0/NC*
SDI1_1/NC*	11	45	SDI1_0/NC*
SDI0_1/NC*	12	46	SDI0_0/NC*
AO_TRIG_OUT	13	47	EXTWFTRG
AI_TRIG_OUT	14	48	EXTDTRIG
GPTC1_SRC	15	49	DGND
GPTC0_SRC	16	50	DGND
GPTC0_GATE	17	51	GPTC1_GATE
GPTC0_OUT	18	52	GPTC1_OUT
GPTC0_UPDOWN	19	53	GPTC1_UPDOWN
EXTTIMEBASE	20	54	DGND
AFI1	21	55	AFI0
PB7	22	56	PB6
PB5	23	57	PB4
PB3	24	58	PB2
PB1	25	59	PB0
PC7	26	60	PC6
PC5	27	61	PC4
DGND	28	62	DGND
PC3	29	63	PC2
PC1	30	64	PC0
PA7	31	65	PA6
PA5	32	66	PA4
PA3	33	67	PA2
PA1	34	68	PA0



ACL-SSI cable for SSI Bus



Wiring terminals DIN-68S/1M

Appendix III. Source code

III.1 Classes

Sensor.h

```
#ifndef _SENSOR_H
#define _SENSOR_H

#include "peak.h"
#include "match.h"
#include "defines.h"

/**
  * class sensor
  *
  * implements a sensor
  *
  * @Author:   Christian Wengert
  * @Date:     7.01.2003
  * @Project:  mc_sonaar
  * @Version:  1.0
  * @ToDo:     -
  *
  * @see       method descriptions
  */
class sensor {
  private:
    int   ID;
    float position[3];
    float orientation[3];
    float raw[SIGNALLENGTH];
    float signal[SIGNALLENGTH];
    int   length;
    peak  *peaks[MAXPEAKS];
    int   peak_count;
    match *matches[MAXPEAKS/2];
    int   match_count;
    int   pir;
    int   oldpir;
  public:
    //constructors
    sensor(int ID, float x, float y, float z);
    sensor(int   ID,   float   x,   float   y,   float   z,   float   thetax,
            float thetay,float thetaz);
    sensor(float x, float y, float z);
    sensor(float x, float y, float z, float thetax, float thetay,float
            thetaz);
    sensor(sensor *s);
    ~sensor();
    void  set(int ID, float x, float y, float z, float thetax, float
              thetay,float thetaz);
    void  set(int ID, float x, float y, float z);
    void  set(float x, float y, float z, float thetax, float thetay,float
              thetaz);
    void  set(float x, float y, float z);
    void  set(sensor *s);
    void  reset();
    void  setPeak(int index, float amplitude);
    void  setMatch(int sensor, int dist, int offset, float cA, float cC);
    float *getSignal();
    float *getRawSignal();
    int   getSignalLength();
```

```
    peak  *getPeak(int index);
    match *getMatch(int index);
    int   getPeakCount();
    int   getMatchCount();
    float getDistance(sensor *s);
    int   getID();
    void  getPosition (float *a, float *b, float *c);
    float *getPosition ();
    float *getOrientation ();
    void  setPir(int pir);
    int   getPir();
};
#endif
```

Peak.h

```
#ifndef _PEAK_H
#define _PEAK_H

/**
  * class peak
  *
  * implements a signal peak
  *
  * @Author:    Christian Wengert
  * @Date:      7.01.2003
  * @Project:   mc_sonaar
  * @Version:   1.0
  * @ToDo:      -
  *
  * @see        method descriptions
  */
class peak {
    private:
        int index;
        float amplitude;
    public:
        //constructors
        peak(int index, float amplitude);
        peak(peak *p);
        peak();
        ~peak();
        void set(int index, float amplitude);
        int getIndex();
        float getAmplitude();
};
#endif
```

Object.h

```
#ifndef _OBJECT_H
#define _OBJECT_H

//definition for classification
#define VIRTUAL     -1
#define UNKNOWN     0
#define POINT       1
#define EDGE        2
#define CORNER      3
#define SURFACE     4
#define PLANE       4
/**
  * class object
  *
  * implements a object for tracking
  *
  * @Author:    Christian Wengert
  * @Date:      7.01.2003
  * @Project:   mc_sonaar
```

```
  * @Version:   1.0
  * @ToDo:      -
  *
  * @see        method descriptions
  */
class object {
    private:
        int     ID;
        float   x;
        float   y;
        float   z;
        float   amplitude;
        int     dim;
        int     type;
        float   confidence_code;
        float   confidence_amplitude;
        object  *next;
    public:
        //constructors
        object(float x, float y, float z, float amplitude, int type);
        object(float x, float y, float z);
        object(object *o);
        ~object();
        //methods
        void    set(float x, float y, float z, float amplitude);
        void    set(float x, float y, float z);
        void    setAmplitude(float ampl);
        void    setType(int type);
        void    setConfidenceAmplitude(float c);
        void    setConfidenceCode(float c);
        float   getConfidenceAmplitude();
        float   getConfidenceCode();
        float   getAmplitude();
        int     getResolvedDimension();
        int     getType();
        float   getDistance(float a, float b, float c);
        int     getID();
        void    getPosition (float *a, float *b, float *c);
        float   getx();
        float   gety();
        float   getz();

};

#endif
```

Match.h

```
#ifndef _MATCH_H
#define _MATCH_H

/**
  * class match
  *
  * implements a code match
  *
  * @Author:    Christian Wengert
  * @Date:      7.01.2003
  * @Project:   mc_sonaar
  * @Version:   1.0
  * @ToDo:      -
  *
  * @see        method descriptions
  */
class match {
    private:
    public:
        int sensorID;
        int distance;
```

```
        int offset;
        float realdistance;
        float confidenceA;
        float confidenceC;
        //constructors
        match(int sensor, int distance, float cA, float cC, int offset);
        match();
        ~match();
};

#endif
```

Generic_Filter.h

```
#ifndef _GENERIC_FILTER_H
#define _GENERIC_FILTER_H

/**
  * class generic_filter
  *
  * implements a digital filter
  * the filter coefficients (IIR or FIR) are stored in the
  * arrays a, b respectively
  *
  * @Author:    Christian Wengert
  * @Date:      7.01.2003
  * @Project:   mc_sonaar
  * @Version:   1.0
  * @ToDo:      -
  *
  * @see        method descriptions
  */
class generic_filter {
    private:
        float *a;       ///array of feedback coefficients
        float *b;       ///array of feedforward coefficients
        int nl;         ///length of b
        int dl;         ///length of a

    public:
        //constructors
        generic_filter(float *a, float *b, int dl, int nl);
        ~generic_filter();
        void set(float *a, float *b, int dl, int nl);
        void filter(float *x, float *y, int startx, int endx);
};

#endif
```

III.2Signal processing

Signal_processing.h

```
/**
  * signal processing
  *
  * Implements all low and high level signal processing algorithms
  *
  * @Author:    Christian Wengert
  * @Date:      7.01.2003
  * @Project:   mc_sonaar
  * @Version:   1.0
  * @ToDo:      -
  *
  * @see        method descriptions
```

```
  */
#ifndef _SIGNAL_PROCESSING_H
#define _SIGNAL_PROCESSING_H

#include "sensor.h"
#include "peak.h"

int     extract_codes(sensor *sensors, int *codes, int n, int bandwidth);
int     find_peaks(int  startx,  int  endx,  sensor  *sensor,  int  subsampling,
float   threshold_a, float threshold_b);

void    trilateration(float *d, float *a, object *objects[], sphere *s1,
                      sphere   *s2, sphere *s3 = NULL, float precision);
float   norm(float *u, float *v, int length) ;
void    analyze_array(sensor *sensors) ;

int     classify(sphere *s1,sphere *s2, float theta1, float theta2);

#endif
```

III.3 Low-level hardware routines

Daq2005.h

```
#include "d2kdask.h"
#include "sensor.h"
#ifndef _DAQ2005_H
#define _DAQ2005_H

void  daq_print_err(I16 error);
void  daq_setup();
void  daq_terminate();
void  daq_start_scan(U16 *ai_buf, U16 *AdId);
void  daq_create_signals(int channels, int *codes, int *schedule);
BOOLEAN daq_signal_sent();
BOOLEAN daq_conversion_done();
void  daq_read_PIR(sensor *s[]);

#endif
```