A Doppler-based motion controller for an echolocating mobile robot

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5.4.2001

Abstract

From the study of biological acoustic sensorimotor systems it can be seen that Doppler is a rich source of information which is not exploited by commercial ultrasonic range sensors such as the Polaroid. In this work we present a simple collision detection and convoy controller for RoBat, a mobile robot provided with a biomimetic sonarhead, based on the presence or absence of Doppler shifts in the received echos while navigating in real life scenarios. Preliminary results using another robot moving along RoBat's path show how exploiting the physics of the robot and the environment before going to higher levels of abstraction results in a simple and efficient way for collision detection and smooth convoy navigation.

1 Introduction

Commercial ultrasonic range sensors, as the widely used Polaroid, do not allow — among other things — extraction of Doppler shifts, which are a rich source of information. We believe that from the study of biological acoustic sensorimotor systems [22, 15], much more information can be extracted from these echoes. Doing so leads to improved robotic ultrasonic sensors, like the one used in this work [20], which mimics the echolocating capabilities of bats. In fact, the relationship between bats and robots arises because the sensor interpretation problems of bats, while navigating in cluttered environments such as forests, are very similar to those of mobile robots provided with ultrasonic sensors when navigating in laboratories. Moreover, the constant frequency pulse emitted by narrowband echolocators (such as the CF-FM bat *Rhinolophus ferrumequinum*) is analogous to the one typically emitted by robotic ultrasonic sensors in terms of bandwidth. Hence, a better understanding of how these perceptual and motor mechanisms actually work in bats could improve the design of mobile robot navigation controllers.

It is believed that CF-FM bats use the Doppler information extracted from the receiving echoes for navigational tasks [14]. In this work we present a simple collision detection and convoy controller for RoBat, a mobile robot provided with a biomimetic sonarhead (described in section 2), based on the presence or absence of Doppler shifts in the received echos.

1.1 Intelligent *vs.* dumb sensors

The use of ultrasonic sensors for mobile robot navigation has been under-rated for many years. Because of the unsatisfying results obtained with these sensors, many researchers became frustrated and decided to used other sensors instead such as vision cameras — which are more expensive and require much more processing time — and laser range sensors among others.

At this point, a question about what was wrong with these sensors arises. The answer is, in our opinion, that most research on ultrasonic sensors for mobile robots has suffered from the 'ultrasonic sensor

Proc. TIMR 01 - Towards Intelligent Mobile Robots, Manchester 2001.
Technical Report Series, Department of Computer Science, Manchester University, ISSN 1361 - 6161.
Report number UMCS-01-4-1. http://www.cs.man.ac.uk/csonly/cstechrep/titles01.html

= Polaroid range sensor' fallacy. This sensor [2], which is used in mobile robotics for determining the proximity of objects, calculates the distance of the nearest reflector present in the sensor operating range through its Time-Of-Flight (TOF). As this sensors operate only on the first echo whose amplitude exceeds a threshold value, most of the information present in the echo signal such as Doppler shifts, incoming echoes from further reflectors, etc is discarded. Even worse, wide beam-width (due to the piston-like transducer's radiation pattern), unwanted reflections (*e.g.* when approaching a concave reflector such as a corner) and diffracted reflected problems contribute to worsen performance when operated in this way. Hence extensive post-processing has to be performed on large numbers of range readings to construct consistent and reliable environment models [13, 11].

In the literature we can find, at least, two well known approaches to the use of ultrasound for navigation in mobile robots: The *grid-map* approach and the *feature-based* approach.

The grid-map approach, which uses rectangular cells as map primitives whose value denotes whether the cell is occupied or empty, was originally proposed by Moravec and Elfes [13]. This idea used a Sonar beam modelled by probability distribution functions. Since then, a large number of papers have further elaborated on the basic ideas [4, 12, 5, 6].

This approach is theoretically well founded and has been widely used. However, there are several weaknesses which make us not to follow this approach. The main one is, we believe, that because of being independent of the sensor — which *a priori* could be an advantage — the grid cell does not correspond with an acoustically meaningful feature of the environment. Even more, since the updating of the grid cells requires constant localisation and, due to the low information rate provided by the Polaroid range sensor, many measurements have to be collected in order to build usable maps.

However, people such as Hallam [7], Leonard [11], Kuc [9] and Lee[10] suggested that reliable range readings can be obtained from Sonar if a realistic model of the sensor is used. In such terms, the feature-based approach emerged, converting range measurements into features available in man-made environments, such as walls, edges, corners, cylinders, etc., using such features as building blocks for constructing maps [16]. This is what we consider the begining of the *good* approach to *intelligent* ultrasonic sensing in mobile robots. Extensions of this approach resulted in different sensor configurations and echo processing [17, 1, 21].

In our work, since we are interested in exploiting the physics of ultrasound, of echolocation, we follow a biomimetic approach to ultrasound-based navigation as described in section 2.

1.2 The physics is out there

In this work we show the utility of using the Doppler information included in the echoes received by a mobile robot when navigating. Our inspiration comes from biosonar, *i.e.* how bats exploit the acoustics of echolocation. The idea underlying in our work with respect to the use of Doppler in mobile robots navigation is that, when moving, dynamically varying acoustic images are generated. These images could correspond, at least in principle, with the images bats get while flying through their environments.

Moreover, one of the interesting aspects of bat biosonar from which we obtained inspiration is Müller's work on acoustic flow for the CF-FM bat [14]. In his work, Müller addresses the hypothesis of an acoustic flow analog to optic flow being used by CF-FM bats to perform obstacle avoidance when tracking an insect in presence of multiple reflectors (*e.g.* foliage, tree branches, etc.). Müller bases his acoustic flow hypothesis on two perceptual dimensions — changes in Doppler shift and sound pressure amplitude — which CF-FM bats may employ for the extraction of two-dimensional spatial information.

The fact that the CF-FM bat modifies — increasing or decreasing — the carrier frequency of its own calls compensating the Doppler shift produced when the bat, the reflector or both are moving indicates the importance of the Doppler shift information in the received echos [26]. Also, CF-FM bats detect interesting properties (*e.g.* food) in echoes, while navigating in cluttered environments, by the frequency modulation patterns produced by the wing-beat cycles of fluttering insects [24, 8, 27].

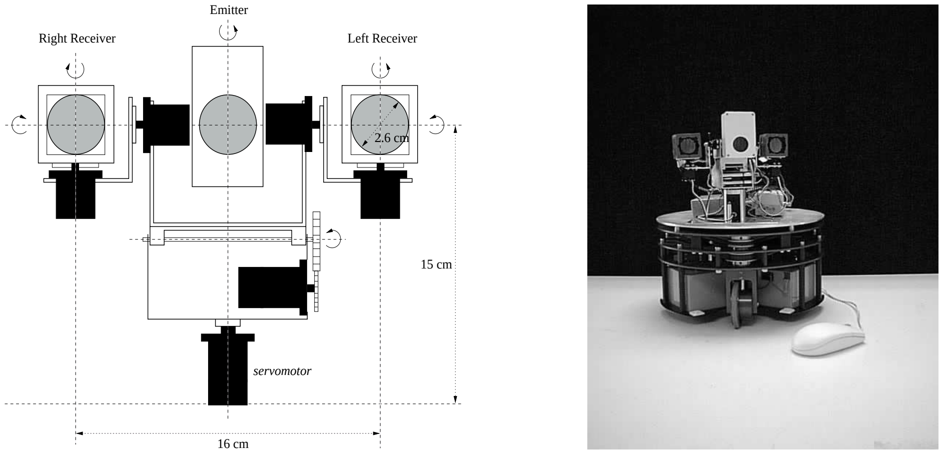

Figure 1: Front view of the sonarhead consisting of the central emitter fixed to the head and the two receivers each independently orientable (left). RoBat, a biomimetic sonarhead mounted on a mobile platform (right).

2 RoBat: an echolocating mobile robot

This work is part of the RoBat project which aims to investigate bat biosonar as a biomimetic approach to mobile robot navigation, *i.e.* tries to understand aspects on how echolocating bats perform navigation tasks such as obstacle avoidance and prey capture, and how can this be applied to ultrasonic-based navigation in mobile robots.

The goals of creating a tool such as RoBat are twofold. It will help engineers to better understand the relationships existing between environment features and their corresponding acoustic images in a dynamic context. At the same time, such a tool will also help biologists studying echolocation in bats better to understand what type of information is available to the bat while performing particular tasks [18].

RoBat consists of three main components: a biomimetic sonarhead (described below), a 3 DOF mobile platform and a modular architecture which integrates a processing module and several behaviours in a reactive way. These three components are all controlled and integrated into a single system by software running on a 1 GHz Athlon PC computer under Linux.

The 6 DOF sonarhead, as indicated in Fig. 1 (left), allows panning and tilting of the neck, and independent panning and tilting of each of the two ears (receivers). The ultrasonic transducers used for the emitter and receivers are Polaroid electrostatic transducers driven with custom electronics. The motors driving the different axes are standard radio-control servomotors [19].

To provide the required mobility to the sonarhead we use the off-the -shelf RWI-B12 mobile platform [23]. This 3 DOF platform has an on-board controller that receives motion commands from and sends back status information to a control computer through its serial port.

This setup, when mounted on the mobile platform (Fig. 1 (right)), allows insonification of arbitrary points in space, independent of the orientation of the mobile platform. Taken together with the capability of the sonarhead to independently orient the ears it allows us to model different strategies that might be used by bats to actively explore their environment [18].

A block diagram of the modular architecture can be seen in figure 2. As seen in the figure, all the monaural modules, such as the signal processing and cue extraction, are duplicated because of the two receivers. The received echoes sampled by an A/D converter are fed into the signal processing module, whose operations are based upon a filterbank model of the processing performed by the mammalian cochlea [25]. The processed data coming from each of the monaural modules is then integrated by the binaural module, resulting in behaviours such as obstacle avoidance, motion detection — a subset of the former — and target tracking. Also, the length and call-frequency of the emitted pulses are recalculated according to the behaviour being performed by the robot at the end of each loop. All processing and

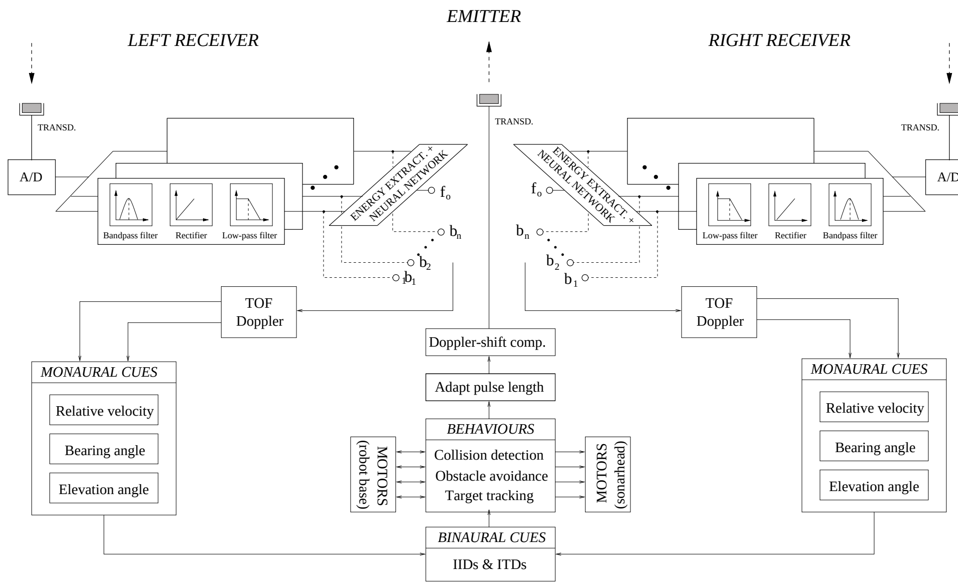

Figure 2: Block diagram of RoBat's architecture.

interpretation of the received data is performed on the control computer, operating at a speed of 12 Hz, *i.e.* 12 complete *sense-and-act* loops per second.

2.1 Obtaining robot-motion induced Doppler shift

In [3] we showed how robot-motion induced Doppler shifts, combined with the echos time-of-flight (TOF), can be used for calculating the cartesian position of a reflector. This is illustrated in figure 3 (left), in which RoBat approaches a post positioned to the right side of its path at a bearing angle α_n. The results of the experiment are shown in the graph of figure 3 (right): Since Doppler shifts depend on the cosine of the bearing angle, a maximum Doppler shift is obtained when the robot is far from the reflector because of the bearing angle between the robot and the post being close to 0° (α_1 in figure 3 (left)). The graph also shows the maximum Doppler shift that could be obtained in the case of the robot's velocity vector being orthogonal to the post. This Doppler shift (maximum Doppler in the graph) is calculated by the following equation:

$$f_d = 2 f_s \frac{v}{c} \cos\alpha$$

where f_d the Doppler shifted frequency, f_s the source frequency (50 kHz), v the relative velocity between RoBat and the reflector, c the speed of sound on air (approx. 345 m/s). However, as expected, Doppler shifts start decreasing while the bearing angle increases (figure 3 (right)) as the robot approaches the post.

In RoBat, the frequency of the principal component of an echo (assuming a single echo signals) from the output of the several channels of the filterbank is extracted using a 6–3–1 backpropagation artificial neural network (ANN). This ANN solves the frequency resolution problem — analogous to the sub-pixel resolution problem in machine vision — achieving a resolution of 1–2 Hz [3]. The reasons for the fluctuations of the Doppler shift and angle values in the first half of the graph in figure 3 are the Doppler shift estimation error of the ANN — which increases with range — and the variations in the mobile platform velocity because of the irregularities of the laboratory floor. The later is not strictly a source of error but of information about the evolution of the robot's velocity along its path.

We are currently assessing other methods such as weighted averages of the filterbank output and different ANN topologies for more robust Doppler shift estimation in presence of noise.

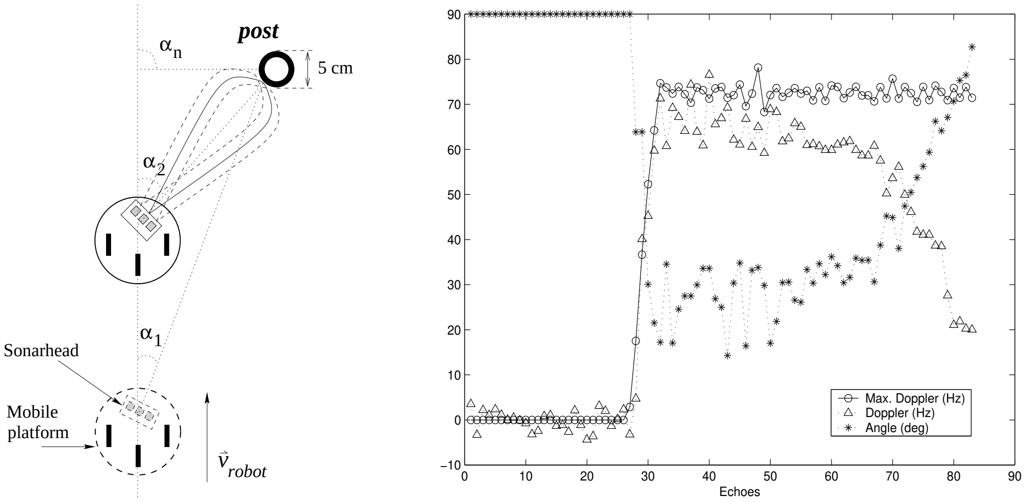

Figure 3: Measurement setup for the acoustic flow task (left). Doppler shifts and angle values estimated by RoBat while driving by a post (right).

3 Doppler-based motion controller

In a real environment, after defining *maximum Doppler* as the the maximum Doppler shift the robot could observe for a given velocity assuming a static reflector at 0° bearing angle, we can find at least three different Doppler-related situations:

- **Doppler $\leq$ 0** There is no reflector in the way or there is a moving reflector whose relative velocity with respect to our robot is zero or negative. In this case the robot can navigate safely within its perceptual range[1].
- **0 $<$ Doppler $<$ Max. Doppler** There is either a static reflector in the way or a moving reflector with a positive relative velocity with respect our robot but with a bearing angle sufficient to avoid a collision.
- **Doppler $\geq$ Max. Doppler** There is a moving reflector in the way with a positive relative velocity with respect our robot and its bearing angle is 0 or close to 0. In this case the robot should change its path immediately for avoiding collision.

Thus assuming that a moving reflector (*e.g.* another robot) is within the robot's perceptual range and at a small bearing angle (close to 0), a simple collision detection and convoy controller, which modifies the velocity of the robot in order to keep the Doppler shift close to 0, can be implemented as shown in figure 4.

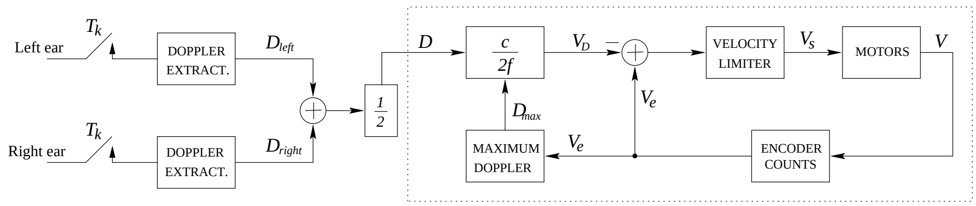

Figure 4: High-level block diagram of the Doppler-based collision controller.

As seen in the figure, after extracting the average Doppler shift (D) from the individual Doppler shifts received by each of the receivers, acording to its sign and value, the velocity of the robot (V_D) is estimated. In case of D being greater than the maximum Doppler (D_{max}), *i.e.* reflector moving towards the robot,

[1]The maximum range from which the robot can accurately sense the environment. In RoBat this range is 3 m.

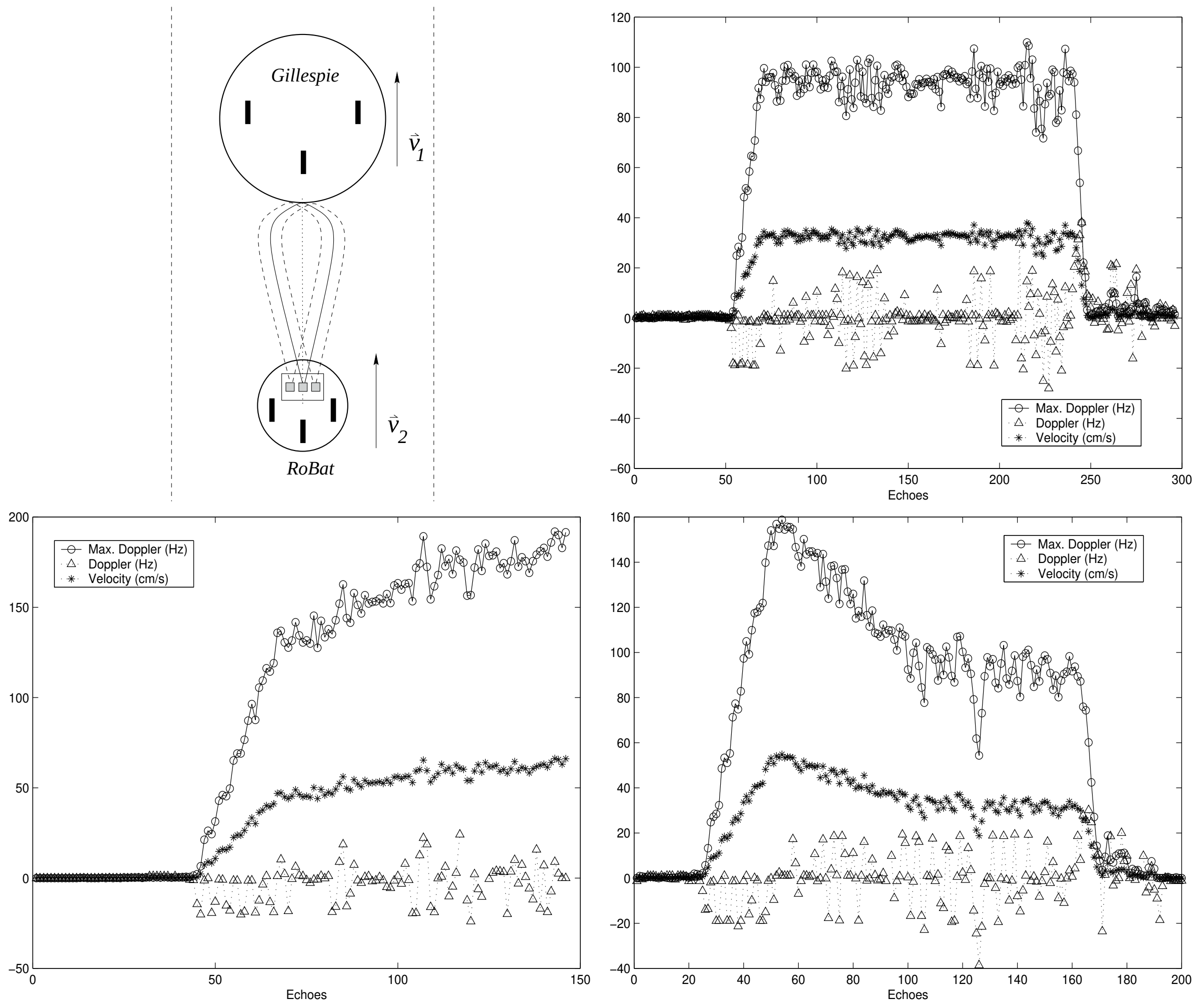

Figure 5: Measurement setup for the motion detection task (upper-left). Doppler shifts and velocity values estimated by RoBat while Gillespie was moving at constant velocity (upper-right), accelerating (lower-left) and decelerating (lower-right).

an immediate escape maneuver such as turning to one side would be adopted for avoiding collision. Next, the velocity is set to its new value (V_s) which is limited by a preset value (60 cm/s). Finally, from the readings of the motor encoders, the current velocity (V_e), which is used for both calculating the new velocity and the maximum Doppler, is estimated.

The experiment designed for assessing the performance of this controller consisted in RoBat moving along a corridor right behind "Gillespie[2]", a RWI-B21 robot moving in the same direction (figure 5 (upper-left)). Three different cases were tested: In the first case, Gillespie starts moving keeping its velocity constant at 35 cm/s ((upper-right graph)). In the second case, Gillespie starts moving and keeps accelerating until reaching the maximum allowed velocity of 60 cm/s(lower-left graph). Finally, in the last case Gillespie starts moving with high acceleration until reaching the maximum speed of 60 cm/s and then decelerates smoothly to 30 cm/s before stopping (lower-right graph).

The controller performed satisfactorily well. For each of the three cases, the Doppler shift, maximum Doppler and RoBat's velocity was estimated for every echo, as shown in the graphs of figure 5. Because of the large size and weight of Gillespie, the irregularities of the floor affect more drastically its velocity resulting in a small ripple as seen in the velocity curve of the three graphs. As in figure 3, this small ripple in the velocity can be clearly seen in the the Doppler and maximum Doppler shift curves.

[2] Since, as Simon Perkins would say, "it's black, round and stout".

4 Discussion

The real world is dynamic, *i.e.* things move and change their position. We believe that for efficient navigation, an agent must take into account other agents moving around in the same environment, and likewise this should be done at the lowest level and, therefore, in the simplest way.

Doppler shifts are a rich source of information which is not exploited by commercial ultrasonic range sensors like the Polaroid. Since Doppler shifts depend on the cosine of the bearing angle between the robot and the reflector, we can assume an angle close to $0°$ for situations in which a moving reflector — *e.g.* another robot – is moving in the same direction within its perceptual range. In such situations, the controller presented in this paper showed how the relative velocity of the other agent can be estimated, resulting in a smooth navigation while keeping the relative velocity close to 0, as seen in the results of the experiments using RoBat and Gillespie.

In summary, this controller is an example of how exploiting the physics of the robot and the environment before going to higher levels of abstraction results in a simple and efficient motion controller for collision detection and smooth convoy navigation in RoBat, a mobile robot provided with a biomimetic sonarhead.

The next step will be the integration in RoBat's architecture of this controller with other behaviours such as obstacle avoidance in the presence of several reflectors and target tracking.

Acknowledgments

Thanks to Yuval Marom for helping with the experiments using the B21 robot "Gillespie". Jose M. Carmena is supported by the European Union TMR Network SMART2 under contract number FMRX–CT96–0052. Facilities for this work were provided by the University of Edinburgh.

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