TRACKING DOLPHINS BY DETECTING THEIR SONAR CLICKS WITH AN ARRAY OF HYDROPHONES

N Morphett, B Woodward and A D Goodson

Department of Electronic and Electrical Engineering, Loughborough University of Technology

1. INTRODUCTION

Considerable numbers of cetaceans (dolphins, porpoises and whales) are caught in nets worldwide as a by-catch of fisheries [1]. Reducing this mortality is both an environmental and an economic issue. At the least, such interactions result in damage to expensive nets and a wastage of fishing time and in the extreme, where cetacean stocks are seen to be at risk, complete closure of commercial fisheries may be legislated.

Cetaceans are believed to use several senses when foraging, which include taste and a highly developed sonar system used primarily for hunting fish by echo location. The sounds emitted can be heard as trains of short clicks when monitored with a hydrophone and a suitable receiver [2,3]. The animals' use of sonar provides a possible method of increasing net detectability, simply by attaching passive acoustic reflectors to the mesh zone [4,5,6]. Other proposed measures to reduce cetacean by-catch involve modifications to the fishing gear, i.e. lowered headlines, inserting escape apertures or the attachment of suitable active acoustic devices to enhance their detectability.

The relevance of the project described here is that the information the system provides should contribute to a better understanding of how cetaceans behave when swimming close to fishing nets. The effectiveness of any proposed 'solution' to the by-catch problem is assessed as an observable reduction in the 'body count' statistics. However the lack of available information on the underwater behaviour of these animals hampers the development and testing of possible solutions. The approach to this problem involved the development of a system for tracking moving sound souces underwater [7-9], in this case the sonar vocalisations of cetaceans. The technique provides accurate information about the movements of cetaceans as they interact with obstacles like nets. Positional information, direction and changes in course, especially when combined with acoustic analysis of the sonar signals, can provide detailed information on the apparent benefit of any proposed gear modification without necessitating large scale trials. For convenience, the early part of this work has been done with bottlenose dolphins (*Tursiops truncatus*) with the intention of extending the studies to include harbour porpoises (*Phocoena phocoena*) in the near future, as in UK waters this species is known to be at particular risk.

2. METHODOLOGY

The basis of the tracking method is to determine the instantaneous position of a dolphin by detecting its sonar clicks. If a click arrives at three spatially separated hydrophones there must be small time delays between the arrivals. By using triangulation algorithms these times can be measured to produce a two-dimensional position fix of the dolphin; using four hydrophones would give a three-dimensional position fix. For this project the aim was to demonstrate the viability of two-dimensional position fixing only because this should be sufficient to obtain useful results.

Of the many systems that have been designed for tracking divers underwater, most depend for their operation on the passive triangulation of pulses from an acoustic 'pinger' carried by the diver. The general principles of diver tracking also apply to dolphin tracking, but there are additional problems, mainly because a dolphin can swim much faster than a diver (up to 10 m/s) and because its click rate may vary from a few hertz to over one kilohertz. If two or more dolphins are echo-locating simultaneously then the individual clicks may not arrive at the hydrophones in the same sequence, which makes the task of triangulating much more difficult.

3. SYSTEM DESIGN

The system design is shown in Fig. 1. The essential function of the hardware is to log the arrival times of the clicks received on the three hydrophones H_1, H_2 and H_3. An arriving click on any channel is converted into a digital pulse by a 'click detector'; the pulse then operates a latch to log the instantaneous clock time under the control of an internal clock. As the click arrives at the three hydrophones in turn, all three latches log the times of arrival. This enables the relative arrival times to be determined and the position of the dolphin to be be computed.

The latch outputs are passed via a Digital Input-Output (DIO) interface card to a computer, which reads the outputs of the latches at regular intervals and builds up a record of the click arrival times. The software analyses the three click trains, associates click arrivals on each channel with the corresponding clicks on the other channels, then computes the source of each click. As the clicks arrive, a succession of position estimates is built up, allowing the track of the dolphin to be determined.

The signals from the hydrophones can be transmitted to the receiver either directly via cables or indirectly via radio waves. Both options were employed during the sea trials phase of this project. The direct method has the advantage that the positions of hydrophones on the sea bed can be determined very accurately. The indirect method uses sonobuoys, which convert acoustic signals detected underwater by a suspended hydrophone to radio signals which are transmitted from an aerial attached to the electronic package floating on the surface. While these devices can be deployed easily from a boat, their positions move under the influence of wave action and tidal streaming. Another disadvantage is that, generally, the batteries need to be removed and replaced at regular intervals.

4. SOFTWARE

The inputs to the algorithm are the time delays between a click arriving at hydrophones H_1 and H_3 measured relative to its arrival at hydrophone H_2 (t_{12} and t_{32} respectively). The solution is a single estimate of the (x,y) position of the dolphin. Other constants required are the coordinates of the hydrophones and the speed of sound in water. For a given pair of delays the algorithm gives one of the following results:

- A single solution;
- A dual solution, of which one will be invalid for the corresponding pair of time delays;
- A dual solution, one real and one a 'ghost', both giving equally valid solutions;
- A solution or pair of solutions resulting from a Newton-Raphson iteration process - required when the solution to a quadratic equation would otherwise contain complex roots.

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The position-fixing algorithm was tested with a number of simulation programs, with the results displayed on a normal PC text-mode screen, i.e. in a rectangle of 80 x 25 characters, equivalent to a physical area of approximately 400 m x 250 m. The triangular array was defined with coordinates of H_1 (-100,0), H_2 (100,0) and H_3 (25,50), i.e. a baseline length of 200 m.

Each point in the 80 x 25 grid was used in turn to generate the pair of time delays (t_{12} and t_{32}) which a real acoustic source would produce. This program involves calculating the distances of the source to each of the hydrophones in turn, converting these into propagation times (t_1, t_2 and t_3) using the known acoustic velocity, then calculating t_{12} and t_{32} ($t_{12} = t_1 - t_2$ etc). The pair of time delays was then used in the program containing the position-fixing algorithms, and the eventual result checked against the original position. This produced a status character, as shown in Fig. 2, where . means a single valid solution, D is a dual solution (both valid), N is a solution requiring Newton-Raphson iteration and X is an invalid solution.

Whilst the dual solution is always mathematically valid, it is usually obvious in reality which of the two tracks is the correct one for an echo-locating dolphin, because of the physically impossible speeds at which the 'ghost' target moves. This led to the notion of a range circle, an area on the plot containing all points which the tracked dolphin could reach. Clearly the radius of this circle is dependent on its maximum speed V_{max} (here, 10 m/s) and the time interval between successive clicks. Using these range circles can eliminate the dual solutions in the majority of cases.

The main problem of the software is to align three varying click trains on three channels without any previous information. However,mathematical analysis shows that if the origin of the acoustic source (the dolphin) is known then for a given click on Channel 2 there is a finite time window on Channel 1 (and similarly on Channel 3) within which a corresponding click *must* arrive.

Generally, the time delays t_{12} and t_{32} change only gradually. Any given click would produce similar delays to the previous click. Analysis shows that the maximum rate of change of t_{12} occurs when the dolphin is moving along the line between H_1 and H_2. The same set of equations holds for t_{32}. This gives the expected time of arrival of a click on Channel 1 as

$$t_2(curr) + t_{12}(prev) - \left(\frac{2.v}{c}\right)\delta t \le t_1(curr) \le t_2(curr) + t_{12}(prev) + \left(\frac{2.v}{c}\right)\delta t$$

which relies only on the last value of t_{12} and the current value of t_2, as shown in Fig. 3.

The width of the time window can be appreciated by putting some simple numbers in: Assume *v* to be 10 m/s, and *c* (the speed of sound in water) to be 1500 m/s. This means that for a dolphin clicking at 100 Hz (δt = 10 ms) a click on either Channel 1 or Channel 3 can be predicted to arrive within a time window of 266 μs. With clicks only arriving every 10 ms there will be no ambiguity about which click on Channel 1 corresponds to a given click on Channel 2.

If the dolphin's click rate is higher, δt falls and the arrival window narrows accordingly, thus providing a self-compensating algorithm which could theoreticall cope with any rate. The program is therefore capable of tracking a dolphin with no clues except for its 'initial position'. If a click is not found where it is expected, the program skips that click and attempts to look for the next one. If none of the succeeding few clicks are found to be where they are expected, the search windows gradually widen until they reach their maximum size. At this point the program is effectively carrying out a full *acquisition*. This restarts tracking from wherever the next source appears. The only further requirement of the tracking system is to locate the starting point by itself; although this can be done it is not described here for reasons of brevity.

5. RESULTS

Several trials were conducted in the dolphinarium at Flamingo Land in Yorkshire for the purpose of testing the prototype system with captive dolphins in a controlled situation. In particular the trials provided the opportunity to try various hydrophone configurations with a view to optimising an arrangement which could be used in later sea trials. The other feature of the trials was to tape record the dolphins' echo location clicks for checking the correct operation of the click detector circuits. The outcome was that both the hardware and software performed well and the overall system design was shown to be viable for future research.

Two of the visits to the dolphinarium used a straight-line three-hydrophone array about 1 m long. This was easy to construct and was held approximately 1 m beneath the surface and against the wall of the dolphinarium, which minimised reflections off the wall. A four-hydrophone array was also used, with the fourth hydrophone held approximately one metre beneath the line of the other three. This arrangement can be used for three-dimensional tracking in future work.

During sea trials in the Moray Firth in northern Scotland, three extended bandwidth sonobuoys were deployed in an area frequented by wild dolphins and clear signals were received on all three hydrophone channels from dolphins echo locating at distances exceeding 300m. The absolute positions of the three sonobuoys were determined using an electronic theodolite from a nearby cliff and theodolite tracks of the surfacing positions of the passing animals is available to validate the underwater tracks. Although the sonobuoy data has yet to be analysed in detail, the groups of recorded clicks have been shown to be out of phase with each other, therefore they can be cross-correlated to obtain the varying time differences necessary to establish tracks. At the present state of development of the system, these tracks can only be determined by post-analysis and at the time of writing (two weeks after the sea trials) this task is still incomplete.

6. CONCLUSIONS

This project has been concerned with the development of a system to track a dolphin underwater, by the use of triangulation algorithms operating on data from three separated hydrophones. The system involves signal processing hardware, digital data acquisition, microcomputer interfacing and computer signal analysis and tracking software. The computer hardware is able to detect dolphin signals from unwanted noise, and to log digitally the arrivals of dolphin clicks at the three hydrophones. The software has been tested in simulations and can acquire and track a single dolphin target completely automatically and, within limits, can also handle multiple sound sources. The results of the three major phases of the project, simulations, dolphinarium trials and sea trials, showed that dolphins - and by extension any echo-locating cetacean - can be tracked using the underwater acoustic system that was specially designed and developed for this application. The project hardware and software still needs some refinement but the basic system has been proven and will be further developed for use in future sea trials with the ultimate aim of understanding more about the behaviour of cetaceans and preventing their by-catch during fishing operations.

7. ACKNOWLEDGEMENTS

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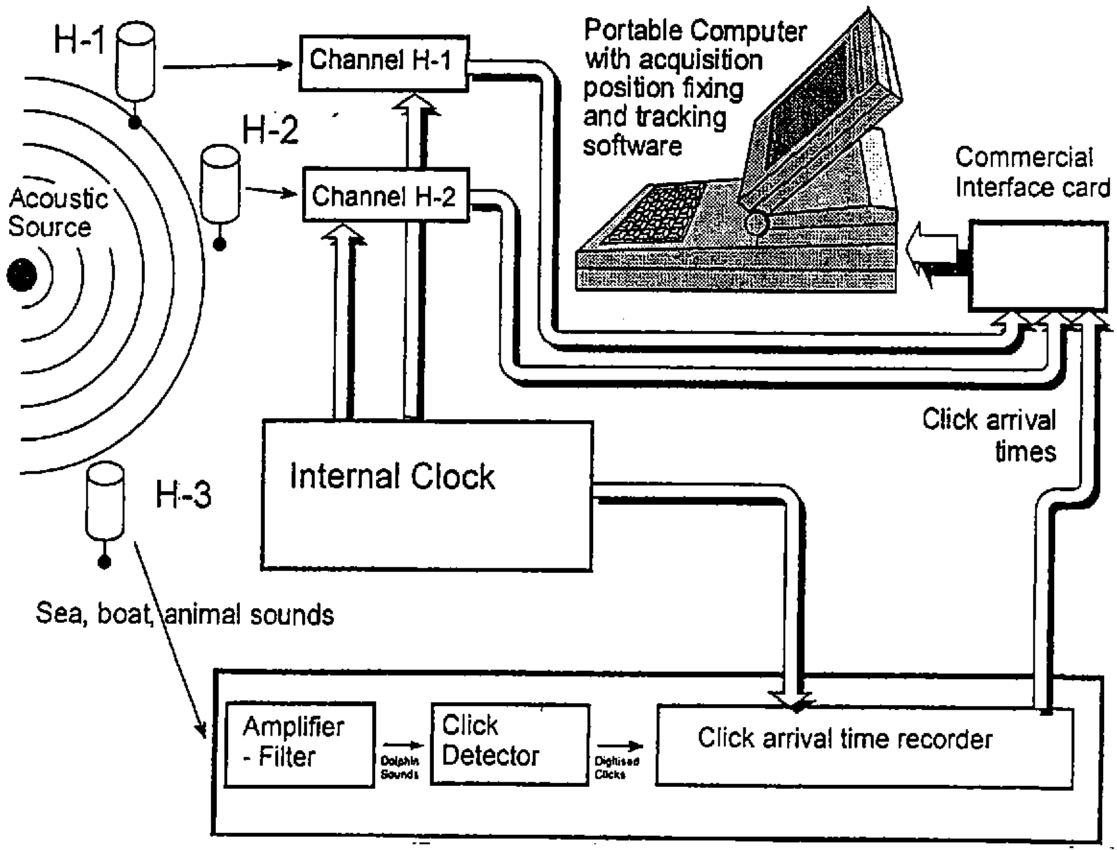

Fig. 1 Underwater acoustic tracking system

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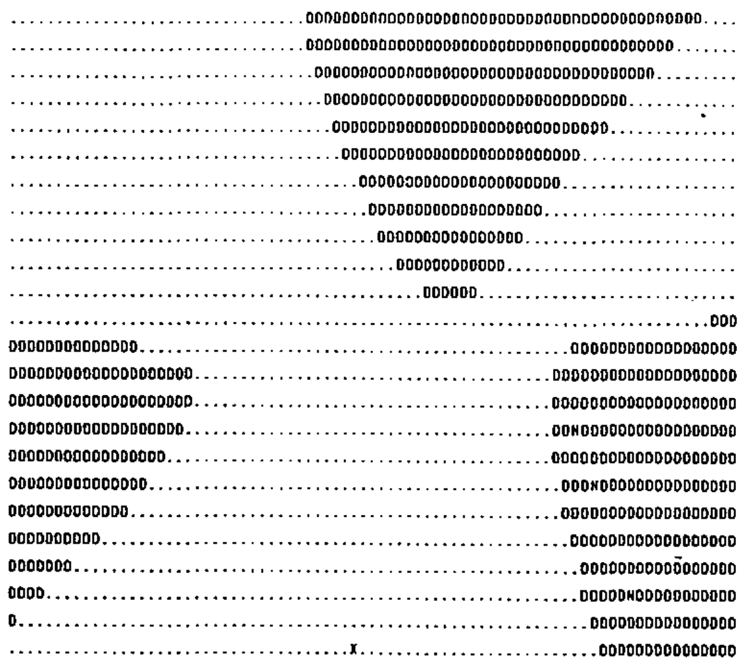

Fig. 2 Algorithm test results

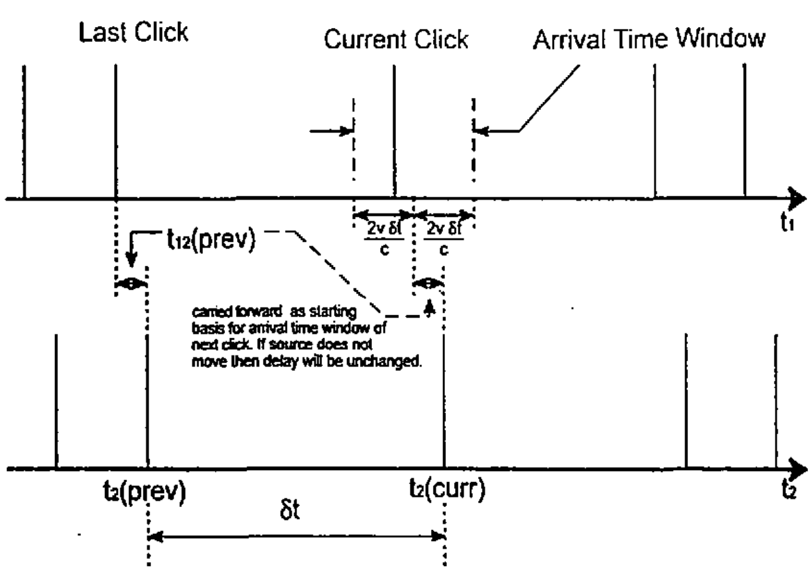

Fig. 3 Channel alignment