DYNAMIC POSITIONING CONFERENCE
September 16-17, 2003

Sensors

Modulated Microwave Position & Heading Reference Sensor

Jan Grothusen

Guidance Control Systems Limited (United Kingdom)

RadarScan – Modulated Microwave Position & Heading Sensor

Abstract

For decades radar has been the principal technology for modern marine safety and navigation and is trusted and relied upon by mariners everywhere. Obviously the advent of global satellite position (GPS) technologies has had an ever-increasing impact and represents an important functional addition to conventional radar. However, as a position reference sensor (PRS) for vessels with dynamic positioning (DP) capabilities radar has never played a significant role whereas GPS is virtually always the system of choice even when assisted by further acoustic, laser or mechanical sensors to achieve the required redundancy. Thus the advantages of radar such as its independence to difficult weather conditions and its ability to provide local reference measurements over significant range have hardly been exploited for DP-controlled station-keeping applications such as diving support, supply vessels and shuttle tankers etc.

This paper presents an innovative microwave radar PRS providing highly accurate local position and heading information for any ship-to-ship or ship-to-rig DP application up to 2km in range. Unlike existing VHF based or active microwave systems this PRS does not require the installation and configuration of cumbersome remote transmitters or relay stations. Instead it uses totally passive, compact, lightweight, low-cost and maintenance-free radar retro-reflectors equivalent to the reflective tape used for laser ranging systems.

Introduction

GCS Ltd. have developed a pre-production prototype marine position reference system consisting of a frequency modulated continuous wave (FMCW) X-band radar rotating about the vertical axis and sweeping out a plane nominally parallel to the sea. It operates at 9.25 GHz with a 100 MHz bandwidth and measures range and bearing to one or more modulated retro-reflective targets. Tracking such targets using an extended Kalman filter the system provides real-time position and heading feedback at rates of up to 4 Hz and is in an operational sense very similar to existing laser position reference systems.

The principal idea is that sensor continuously measures range and bearing to beacons of a priori known position or relative geometric constellation to allow for local position and heading estimation. The modulated retro-reflectors maximise return energy in the direction of the sensor and provide a coded return signal to allow for discrimination from background clutter as well as between different reflectors. Unlike traditional RACONS the modulated retro-reflectors are "passive" in the sense that they do not transmit themselves but only reflect incident electromagnetic energy and are therefore both low-cost and low-power.

The radar system has a minimum and maximum range capability of about 20 m and about 2000 m respectively. Range and bearing resolution of about 0.1 m and 0.1 mrad can be achieved. Like conventional radar systems the system is mainly immune to environmental conditions and can operate in cluttered environments.

Overview

The system (see Figure 1) provides a single rotating antenna mounted inside a low loss radome transmitting a pair of vertically polarised frequency-modulated continuous-wave (FMCW) electromagnetic signals of dynamically adaptable sweep ranges depending on the range discrimination required. To achieve the required front-end isolation the respective dual receiver feed chain is aligned for horizontal polarisation. The cross-polarisation of the transmit signals and the receive signal is crucial as it prevents power leakage between the transmit and receive feeds at the antenna end, which would otherwise be significant in an FMCW radar system. It is the responsibility of the transponder to ensure that the required change of polarization is achieved when retro-reflecting the incident electromagnetic wave front to the sensor.

As shown the radar system is capable of simultaneously processing the receive signal from two or more transponders which is a necessity in order to provide local heading information in addition to the normal position information. At least three measurements are required to solve for the three unknown in which case two range and bearing pairs provide sufficient information.

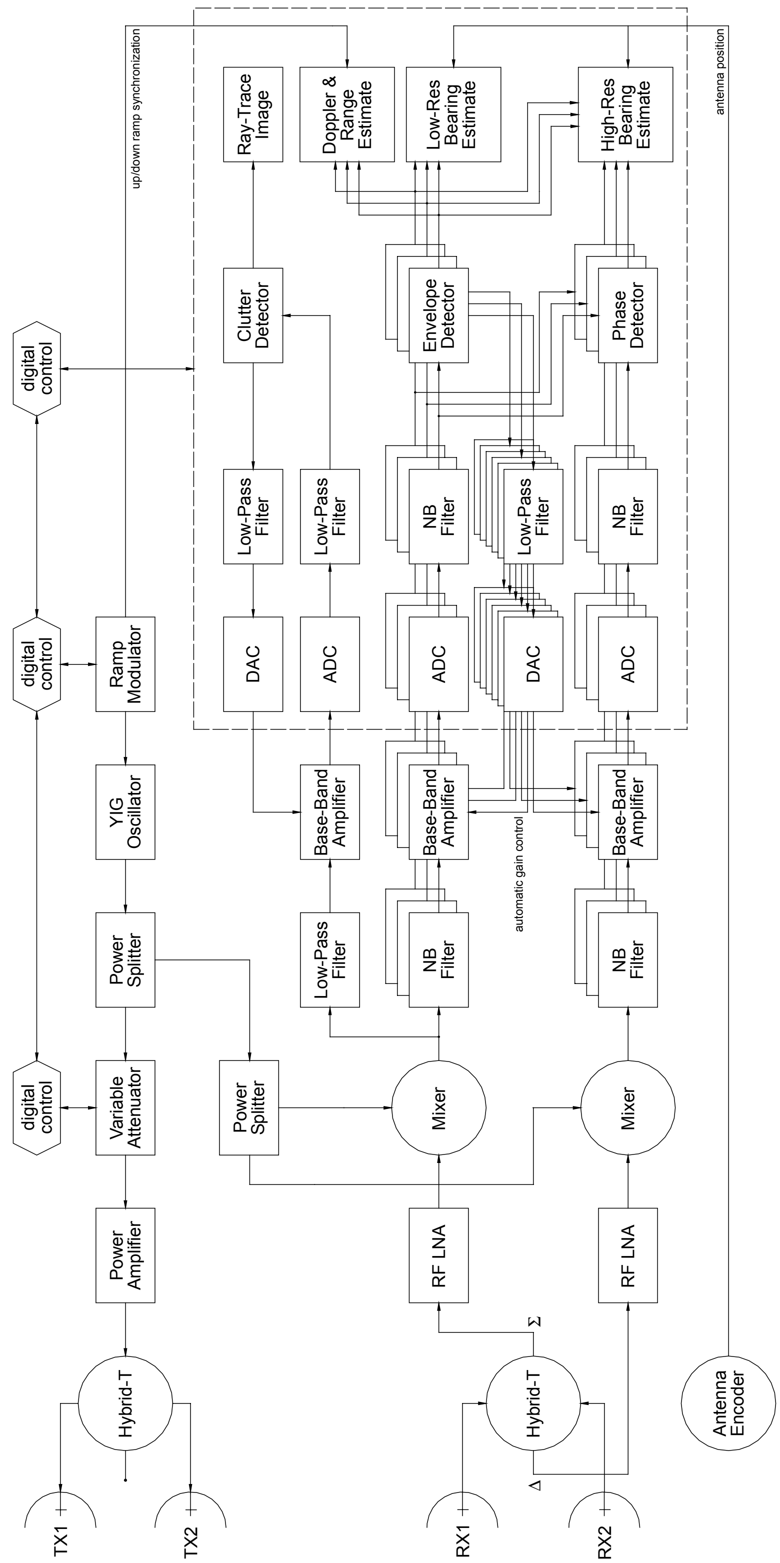

Figure 1: Radar Functional Schematic

The transponders operate at different modulation frequencies and thus superimpose unique temporal codes on the incident transmit signals so that the radar system can easily distinguish between the receive signal from one transponder and the receive signal from another transponder. Equally important, the modulation also helps the radar system to discriminate the receive signal from the background clutter and for example allows to detect transponders against a background of steel which would otherwise saturate the front end receiver chain.

Additionally, as a result of having two transmit feeds the radar system can use monopulse techniques to determine a bearing estimate to the transponder on a "per sample" basis in order to reduce the risk that background clutter will seriously degrade the achievable angular resolution. Monopulse is a standard radar technique but is normally only used for antennas that lock on to a target during operation. Applying monopulse techniques to a rotating antenna has been found to give an improvement in the amount of information that can be obtained in a single scan to obtain a better bearing estimate.

It is generally accepted that monopulse techniques do not work well if two targets are close together. However, because of the unique transponder codes they can be easily distinguished from each other regardless of their spatial separation. The bearing estimate obtained using the monopulse technique can be used in combination with information about the angular position of the antenna developed using an optical encoder, for example.

Transponder

The principal design choice to opt for a retro-reflector type system and not an active kind of transponder (eg RACON) was based on the need to avoid a permanent remote power source. Unlike other RF positioning systems employing active remote stations with permanent power supplies retro-reflective transponders can be treated like low-cost, discardable and maintenance free targets such as the retro-reflective tape used for laser systems. They do not require any setup, tuning or configuration bar the basic fixing at the remote vessel (eg oil rig) within clear view of the operational area.

Traditional retro-reflectors, often used as radar target enhancers for yachts and small crafts, are derivatives of corner-cubes or Luneberg lenses. However, they all suffer from their bulkiness as well as the sometimes insufficiently broad incidence angle performance or deep nulls in their radar cross section (RCS). Instead a Van-Atta (US patent 2,908,002) type approach was chosen in a printed circuit-board (PCB) implementation similar to conventional patch array antennas. A Van-Atta array (see Figure 2) operating in the far-field reconstructs the incident electromagnetic wave front sampled at apertures 1–6 when counting equal path lengths from points A–F, B–E, C–D and reverse based on equal length transmission lines.

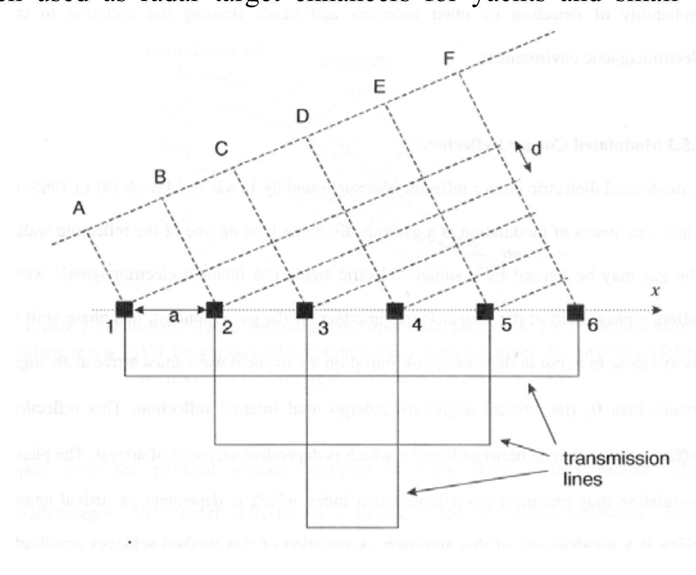

Figure 2: Van-Atta Schematic

For all practical purposes the equal transmission line length restriction has serious implementation problems. Fortunately this has been overcome by breaking this requirement and replacing it with a more flexible wavelength constraint, which has the side effect of making the Van-Atta array frequency selective (patent application WO 00/59068) and making PCB implementations possible. Separate PCBs contain the radiating elements and interconnecting wave guide tracks and modulation electronics.

The preferred solution is a flat panel similar to a patch antenna with square patches as radiating elements arranged in symmetric sub-arrays (see Figure 3) and coupled with slot-coupled transmission lines in a two laminate assembly.

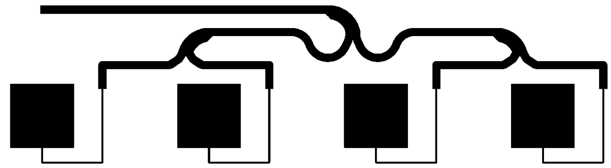

Figure 3: Radiating Sub-Array

Such elements can be optimized for their frequency response and polarization to ensure perfect operation with the radar system without affecting other radar systems. More importantly the azimuth and elevation gains can be traded-off against each other to achieve the optimum RCS in each direction. Based on the effective area of the sub-array elements the theoretical peak gain can be calculated at around 8 dBi however this hides the more important fact that in the vertical cut the RCS is purely defined by the aperture of a single square patch and therefore results in a very favourable flat and broad response (±60 degrees, see Figure 4). In the orthogonal cut direction, corresponding to the elevation illumination, a much narrower (±10 degrees) half-power beam width is a result of the aperture of the overall sub-array. Extrapolating the gain figures for the sub-array an overall RCS of $5m^2$ can be achieved with a total of 40 sub-arrays over the small area of 350mm x 220mm. Other configurations with even higher overall RCS figures can be achieved.

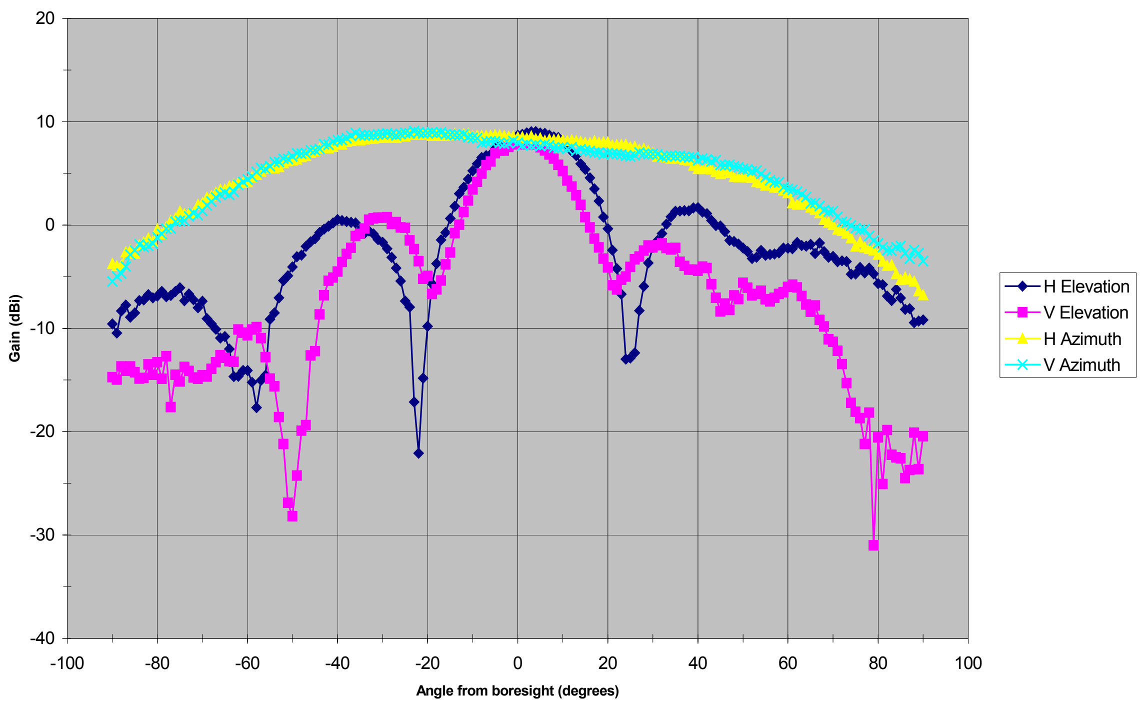

Figure 4: Gain with bore-sight for each polarization

The superimposition of a unique temporal code onto the retro-reflected energy is achieved by the incorporation of suitable high-frequency pin-diodes directly onto the wave-guides etched into the board laminate (see Figure 5). Thus phase or amplitude modulation are equally feasible, while the former is the simplest when employing digital monotone modulation as this has the added benefit of suppressing half the sidelobes. Very little power is required for this purpose allowing long-term operation on a small embedded battery as the pin-diodes can be switched with only a few µA of bias current. The use of sub-arrays has the added benefit of reducing the number of transmission lines, the overall return losses and the number of pin-diodes required, so that only a small number of diodes need to be employed even in modest transponder assemblies. Care needs to be taken to reduce the insertion losses and to ensure no RF leakage into the driver circuit consisting of a small number of standard CMOS semiconductors.

Radar Sensor

With reference to Figure 1, the radar system is driven by a YIG oscillator providing a 9.2-9.3 GHz (X-band) signal which is modulated by a DAC ramp modulator and fed through a power splitter, a variable attenuator and a 35dB power amplifier to a hybrid T where it is divided to create the two transmit feeds TX1 and TX2 in vertical polarization.

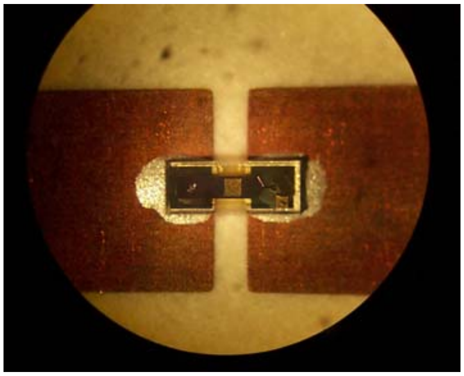

Figure 5: Microscope view of diode

The reflected signal is received at the rotating antenna by two spatially separated receive feeds RX1 and RX2 and combined in a hybrid T giving a Σ and Δ output. The sum output and the difference output are fed into separate mixers where they are mixed down with the transmit feed from the power splitter to the intermediate frequency (IF) stage. The IF signals are filtered using narrowband 0.5 MHz filters to remove background clutter and to separate out the signals returned by each of the transponders, amplified using base-band amplifiers and fed into a quad-DSP system. The passband filters are specifically chosen to match groups of different transponder modulation frequencies.

The mixed signal from the sum output is also filtered using a low-pass filter to isolate the background clutter and amplified using a base-band amplifier. The processing system uses this signal to produce a 360° trace image which can be used to provide a background image on the operator display giving a visual ray-trace of the environment.

The filtering and amplification is carried out separately for each of transponder modulation frequencies and the filtering and amplification can be hardware or software based depending on the degree of flexibility that is required and the processing power available.

The usual pre-filtering, down-conversion, normalization and frequency analysis is performed to determine a range and bearing estimate. The processing is carried out using an envelope detector and a phase sensitive detector, both of which use information about the angular position of the antenna developed by an optical encoder. Analysis of the power spectrum in the frequency domain (see Figure 6) clearly shows the up- & down-ramp peaks corresponding to individual transponders.

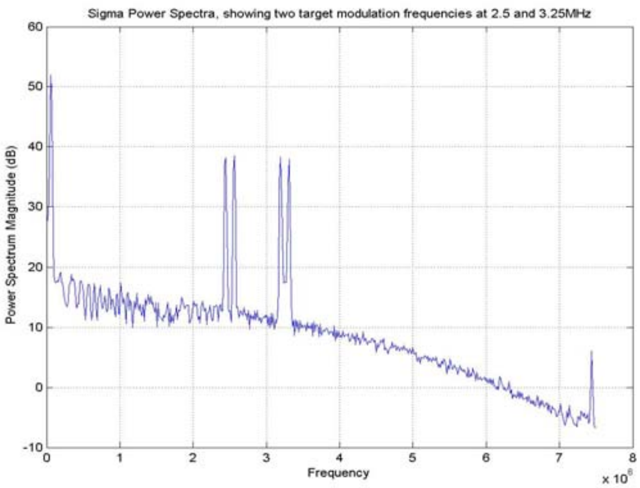

Figure 6: Two target power spectrum

The frequency difference between the two peaks centered on the nominal modulation frequency corresponds directly to the range to the target as in conventional FMCW systems (see Figure 7) and can be recovered using standard FFT and constant false alarm (CFAR) analysis techniques. The bearing estimation operates similarly except that because of the monopulse approach glint effects can be reduced and the standard optical encoder resolution can be improved upon by performing zero-crossing analysis of the phase sensitive detector output as well as integrating the envelope detector output.

The transponder modulation products are deliberately spaced to avoid cross contamination with low range clutter while staying within the bandwidth capabilities of the transponder (see Figure 8).

The clutter rejection performs well and can even cope with narrowly spaced targets where due to the antenna beam width both targets are simultaneously illuminated across a sweep (see Figure 9).

The DAC ramp modulator produces a saw-tooth analogue ramp signal, which is used to derive a digital direction signal and fed into the processing system to determine the velocity of the antenna relative to each of the transponders using Doppler techniques.

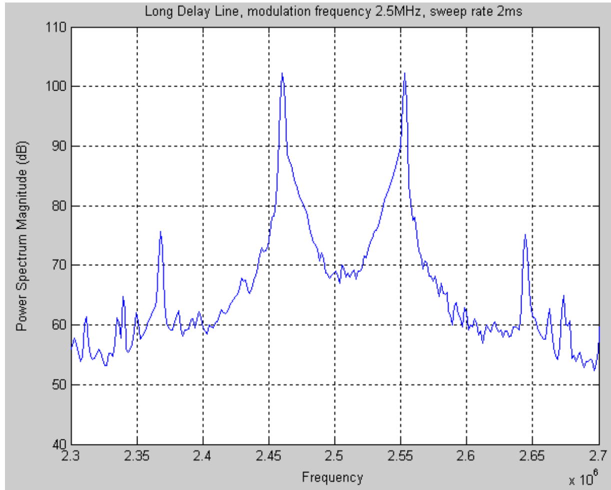

Figure 7: Target at 130m range (Δ ±40 kHz)

The system can thus not only resolve position and bearing to a number of unique transponders but also velocity vectors in the direction of each target. This can be combined in an extended Kalman filter to track the targets taking account of wave motion and vessel ego-motion to provide an accurate and real-time local position and heading update at up to 4 Hz. The discussion of these DSP algorithms and the Kalman filter are beyond the scope of this paper.

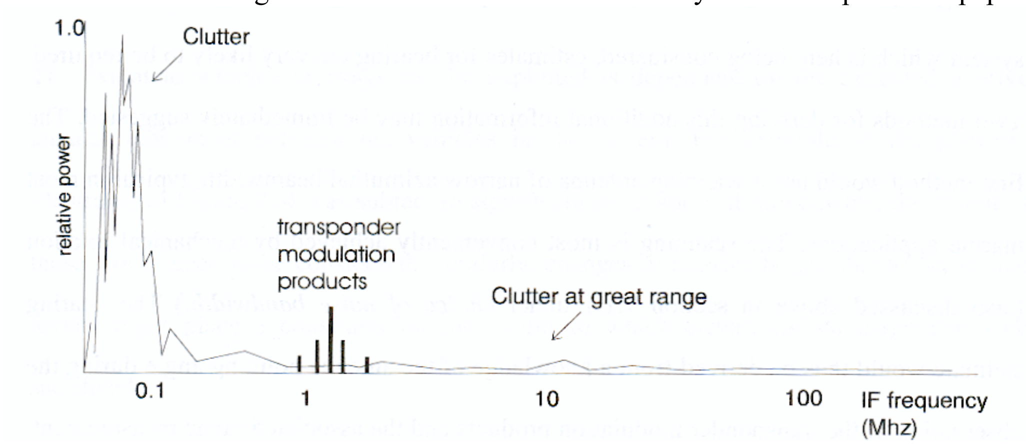

Figure 8: IF spectrum

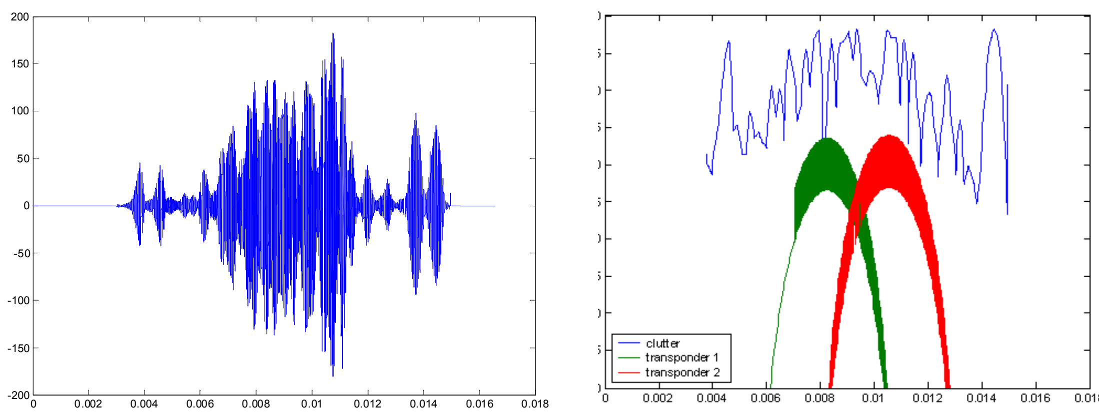

Figure 9: Time domain waveform and power spectrum analysis of two narrowly spaced targets against a background of radar clutter.

Conclusions

The sea-worthy prototype implementation has 5W of transmit power and is fully enclosed in a sealed radome (see Figure 10) and fitted with a heater and pressure compensation seals. The embedded real-time control system is based on four low-cost 100 MHz DSPs with 600 MFLOPs each, two 65 MS/s 12-bit A/D and a 100 MHz FPGA front-end integrated into a single board coupled with an embedded PC on a common PCI interface. The PC is responsible for running the actual navigation algorithms and a networked user-front end while the DSP front-end controls the data acquisition and the real-time number crunching. The system is expected to be undergoing sea-trials by the time of publication with production engineering commencing forthwith.

Figure 10: Prototype (housed and open) prior to sea-trials

Contact Details

For further details please contact in the first instance the author, Jan Grothusen, at:

Guidance Control Systems Ltd.
4 Dominus Way
Meridian Business Park
Leicester, LE19 1RP
United Kingdom

Email: jan@gcsltd.co.uk
Web: www.gcsltd.co.uk

Phone: +44 (0)116 229 2603
Fax: +44 (0)116 229 2604