Abstract
This paper presents experimental results obtained in ‘OxNAV’, a 3-year research project investigating autonomous vehicle navigation systems. The project aimed to develop navigation systems for low-speed, continuously moving, indoor vehicles suitable for industrial use. Research addressed on two main issues: validation of distributed control algorithms for wheeled vehicles, and development of distributed filtering and sensor management algorithms capable of ensuring robust reliable operation in the presence of noise and clutter. The work presented in this paper focuses on the results obtained in lengthy experimental trials at active industrial sites and in the laboratory. Details of the system architecture and theoretical advances in distributed Kalman filtering that contributed to the results presented here have been previously published in [1,3,4,5,8,9,14].

1. OxNAV Localisation System
The OxNAV system’s primary sensor is differential time of flight sonar [4,6,7,10]. Continuous localisation of a moving vehicle is achieved with this relatively slow sensing technology by using a directed sensing strategy. Instead of scanning the whole environment, the system uses rapidly steerable sonar detectors to lock onto and track a few particularly well defined features. These target sonar features (or, sonar targets) are selected from a prior map of the environment provided by the user. Thus, although no beacons are required, the OxNAV system navigates by observing the positions of fixed, known, targets. Location estimates are derived by fusing target observations, prior map data, and odometric information using an extended Kalman filter (EKF) [2] algorithm. The localisation filter is supported by sophisticated sensor management and data-association algorithms that control sensor data gathering. These ensure that only well defined targets likely to produce good positional information are selected (reducing noise sensitivity), and that sensor data likely to be associated with features other than the selected targets is rejected (reducing sensitivity to clutter).

1.1 Architecture
The OxNAV localisation filter is implemented as a distributed extended information filter (EIF) [2,8]. This allows it to ‘partitioned’ to support an efficient distributed implementation across seven processor nodes - one node for each sonar sensor or wheel controller. The processor nodes are physically integral components of the sensor / actuator modules. The sensor sub-system of each sonar module comprises four major components: the tracking filter, target predictor, target validator, and tracking manager. The target predictor’s job is sensor management. It selects sonar features as targets for tracking that are (a) likely to be detected and (b) placed so that observations will minimise positional uncertainty. It accomplishes this task using a novel information-theoretic algorithm based on estimation of the mutual information between estimated vehicle location and target obser-
The OXNAV target validator is responsible for data-association. It detects and rejects sensor data likely to be inconsistent with the target selected for observation. It employs a combination of geometric checks and a standard information-theoretic validation gate [2] using the sensor observation model of the localisation filter. The Tracking Manager (TM) triggers the selection of a new target when tracking is lost, data association is unreliable, or the gimbal limits of the sensor are reached. In performing this task the TM employs a focus of attention strategy: once established, a target is tracked until it is repeatedly rejected by the target validator and an alternative found by the target predictor.

Figure 1 shows the internal architecture of a sonar processing node indicating. The computations is partitioned between so that computations involving the sensor model $h$ (filter correction, target prediction and validation) are all performed together by a single server process. This allows the (expensive) computation of $V, h$ to be shared between the filter calculation and sensor management and permits the prediction and correction phases of the filter calculation to be performed partly in parallel for maximum throughput.

Target selection, and validation algorithms are presented in detail along with data motivating the TM strategy.

2. Experimental Results and Methods

System testing through extensive trials in active industrial sites formed a major part of the OXNAV project. These trials utilised a modular AGV developed specifically for the OXNAV project [1] (see Figure 2) and involved over 100 hours of vehicle running time. Through these trials we have obtained a great deal of data on the performance of the OXNAV system, both as a whole and its various hardware and software components.

2.1.1 Trials Programme

The trials sites covered a postal sorting office $S$, a residential nursing home $R$, a heavy vehicle factory $F$, and a working office $O$. An office corridor $C$ was also used. The trials sites were deliberately selected to be as varied as possible, to avoid the possibility of particular environmental characteristics hiding flaws in the navigation system. The residential environment, for example, provided a mix of targets ranging from easily navigable corridors to sonar ‘no go’ areas surrounded by soft furnishings with no visible permanent targets. The industrial site, by contrast, provided a pitted concrete floor with a very high level of ambient noise. In between the two, the office was characterised by many good targets but also significant clutter. The sorting office had many impermanent sonar features.

A typical trial comprised the mapping of several hundred square metres of trials space, followed by two or more days testing a wide variety of runs through this space. Example trial site maps are shown in Figure 3. All sites were ‘live’ and in constant use during the trials period, and thus subject to normal levels of change and human clutter. Operating speeds for the OXNAV system are currently restricted to 0.25 m/s, with 0.20 m/s usual for trials. The RCDDs are, however, capable of tracking targets while moving at up to 0.4 m/s, sufficient for commercial indoor applications. Higher speed would, however, require a more complex plant model then is currently implemented.