Laser Guided Vehicles, LGV's:
Industrial Experiences and Needs for the Future

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Abstract
Freely navigating vehicles using directions to identical retroreflective tapes has been in industrial use since 1991. In this paper we give
- some experiences from more than 5000 *installations*, in industry, in mines, harbours etc
- outline the AutoSurveyor that *automatically* gives a map of the reflectors, SLAM.
- mention Teach-In where the robot, by a manual operation, learns the trajectory from, say, a loading station to the "navigation highway".

Among needs for the future we mention
- The need for sensing obstacles. This also includes objects hanging down from the ceiling!
- Sensing and navigation in cases where retroreflective tapes *can not* be used.
- Outdoor sensing that is robust booth to snow flakes, hoarfrost, rain and bright sunshine.

It is very essential that the vehicle / robot have reliable and predictable properties. This is both a question of safety and economy. The paper outlines some properties and discuss the future.

Keywords: navigation, retroreflective tapes, landmark association, auto surveying (SLAM), teach in, multi-sensor systems, association errors, robustness

1. Introduction – identical beacons
The basic idea behind the LazerWay™ navigation system is beacons using retroreflective tapes. The angles to the navigation beacons are detected in a *robust* way since the illuminating laser and retroreflectors gives a very good S/N ratio. A typical error is 1 milliradian.

Indoors, the navigation repeatability is typically +/- 2 mm at a speed of .5 m/s. In mines with Load-Haul-Dumps, LHD, the repeatability is a few centimetres at 20 km/h. A large LHD is 80 tons with 25 tons load. The wheels are soft and the steering articulated. No rate gyros.

In many applications there are the "navigation highways" and loading stations. By, say, a manual operation the robot can *learn* the trajectory - a Teach-In procedure. More details on early results can be found in [Hyy87] while [NDC] gives user info. It should be mentioned that this principle was used earlier to detect stars with optronics onboard *spinning* sounding rockets. The pattern of the detected stars was used for finding the *attitude* of the rocket along the trajectory.

2. Automatic Generation of the Reflector Map (SLAM) – AutoSurveyor
During early tests the reflector map was measure manually using teodolites! Of course, an automatic map generation method is needed. An algorithm solving the large number of non-linear equation was found in 1991 and the AutoSurveyor went into industrial use 1993. A fully automatic version AutoSurveyor II was launched in 1996. More details on these early cases of SLAM can be found in [Åst 91, 93] and [ÅstO 00].

3. The Association Problem – Ambiguities

Given a reflector map and a vector of detected angels. Since the reflectors are identical, the problem is then to match them together, the association problem. Using a data driven state estimator, missing occluded reflectors are not a problem. One bad case is if a false detect is associated with a reflector in the map. Another bad case is if detects are paired together in a wrong way. Thus, a large number of reflectors is not good since it increases the risk of association errors.

To illustrate the non-linear nature of the problem consider just two reflectors observed by the robot. Since there is no compass onboard, only the difference in angle carries useful information. The position uncertainty for the robot is the circle going through the two reflectors and the robot. This have in fact happened in practice, the robot was running and stopped. All reflectors except two were occluded. Due to linearization err's in the Kalman filter the estimate started to move along the mentioned circle. When the occlusion disappeared and the robot was to start again it was lost since the orientation drifted away! We conclude by mentioning some "facts"; The *combined* problem of association and state estimation is outside the framework of the Kalman filter. If the linearised estimator is used, the association uncertainty introduces *additional* terms in the Riccati equation.

4. Conclusions, needs for the future

The strength of this is reflector based navigation is *both* the *S/N ratio* in the detector and a *direct sensing* of the *orientation* of the vehicle. In many applications we can not use reflectors or beacons. How should we use multisensing (lasers, cameras and gyros) to build a reliable system? When the vehicle moves a few times it's own length it has to make a decision. This requires an error rate $<10^{-6}$ in many cases!

Using lasers and cameras it is possible to extract robust features from geometrical primitives like walls, corners, tree trunks etc. Navigation will then be relative to these landmarks. We also need a good angular stability. A rate gyro can do this job. For LaserWay the directions to the reflectors (+/- 1 millirad) gave the angular stability for the vehicle. Recall that the LHD's could navigate without rate gyros. It is very essential that the vehicle / robot have reliable and predictable properties. This is both a question of safety and economy. This application area is also in need for better theories to give model based self monitoring control systems.

References

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