Evaluation of Navigation System Performance Requirements for Safe Autonomous Navigation.

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Abstract. This paper describes how different motion sensors can be integrated and fused to obtain necessary navigational requirements needed for autonomous operations. Both autonomous coastal navigation and automatic docking operations are analysed with respect to trade-offs in position and velocity accuracies, integrity, availability and continuity. By using AIS measurements from typical docking operations for the Norwegian coastal express vessels it is possible to define feasible safe trajectories for the docking operations. Justified requirements can be obtained using closed-loop analysis for the specific vessel and its operation. Both vessel and passenger safety can be related to vessels horizontal velocity and the safe velocity concept has been introduced to derive requirements for integrity, availability, alarm limit and continuity in case of unreported/unhandled errors in the navigation system. The outcome of this study is a design tool, or a generic methodology for selecting the most promising combination of the integrated sensor components to obtain necessary navigation system performance for safe autonomous navigation.

1. Introduction
This paper describes a methodology for deriving justified technical requirements for the position, velocity and timing (PVT) sensor solution to be used for autonomous navigation. Two different autonomous operations have been investigated: autonomous coastal operation and automatic docking. Based on existing AIS data from the Norwegian coastal express vessels, feasible trajectories with corresponding accuracies for both positions and heading are obtained from several docking operations. When vessel is moored at the quay, also the accuracies for both position and heading are analysed and will be used as input to a noise model when analysing the closed-loop control system. Based on the IMO requirement [1] for position accuracies for automatic docking operation, we propose to justify the requirements to also include requirement for the heading measurements and also the velocities (surge, sway and yaw motion) to obtain required accuracies for closed loop control. Since the vessel is docked manually today, we propose to use the measured trajectories as a requirement for the closed loop control as well. Closed loop control requires that the vessel will follow a desired feasible trajectory which again depends on the actual vessel propulsion configuration and desired closed-loop behaviour. The IMO requirement of 0.1 m horizontal accuracy which is related to accuracy of the position measurement, is not necessarily needed in closed loop control to obtain a motion accuracy of 0.1m in for a selected position on the real physical vessel due to the nature of a closed-loop control system.

2. Selected autonomous operations
Typical concept of operations for the coastal express vessels is presented in Figure 1. During undocking and docking operations, GNSS augmentation service (SBAS, GBAS) will give better position accuracies than during the coastal operation. For the coastal express vessels travelling along the Norwegian coastline, the GNSS augmentation system is available for most distances. Since the navigator and captains on the coastal vessel have permission to dock the vessel themselves, there is no need for external piloting. Typical position accuracy requirement for the navigation in coastal areas should be better than 10 m and for the docking and undocking case, the requirement should be much lesser than 10 m. These requirements are rather generic and must be further analysed and adopted to case by case.
2.1. Autonomous coastal navigation

During coastal operation, only the main propulsion units are used, not the bow thrusters. The navigator uses the waypoint tracking control function to follow a desired track from the ECDIS system by use of rudder. Typical, feedback signals to the controller are position measurements from GNSS and heading/rate of turn. The vessel speed is still controlled manually. If there is a need for an evasive manoeuvre, the navigator needs to do this manually. For an unmanned, autonomous coastal operation, both own vessel's position (localisation) and the surrounding objects must be identified and used as input to the control system. By fusing cameras and radar images or other sensors it is possible to detect and identify critical objects with properties like speed and geometry that has to be digitized in same manner as human situational awareness (perception, comprehension and projection). Maritime situational awareness is still an uncovered and new research field. Replacing human on bridge with computers is difficult, but it is possible to use available navigation data to assist navigator performing safe operation as a first step. In the EU project Hull-to-hull [3], the concept of uncertainty zones is introduced. The uncertainty zone is the outer boundary of the vessel based on GNSS, heading and simple geometry description of the vessel, see Figure 3. Since the AIS data contains a specific position, course over ground and heading, it is possible to compute vessel's own outer boundary with probability. In addition, by transmitting GNSS raw data between several vessels, it is possible to derive relative distances and velocities for neighbouring objects with high precision and high integrity.

Figure 1. Internal/external information demand and support by services for ship navigation, [2].

Figure 2. The Norwegian coastal express vessel MS Polarlys.
2.2. Automatic docking

Analysis of AIS data from the docking operation:

As a part of the study, analysis of AIS data that has been performed during this task to be able to calculate the relation between the distance to the quay and the ship's speed and heading during a port approach. AIS data from one year for the Port of Trondheim covering the docking of the coastal expresses MS Polarlys (Figure 2). MS Nordnorge and MS Trollfjord has been used. MS Polarlys and MS Nordnorge are both RoPax ships with length 123 meters, width 19.5 meters and gross tonnage 11300, while MS Trollfjord has a length of 136m, width 21m and gross tonnage 16100. These vessels operate on the coastal express route between Bergen and Kirkenes, including port visits to Trondheim both on north- and south-bound voyages. The reported AIS position is referred to a specific location on the vessel and is obtained from one of the AIS messages. It is reported as 4 distances in Table 1.

| Coastal express | To bow (m) | To stern (m) | To starboard (m) | To port (m) |
|-----------------|-----------|-------------|-----------------|-------------|
| MS Polarlys     | 33        | 90          | 3               | 15          |
| MS Nordnorge    | 47        | 76          | 14              | 10          |
| MS Trollfjord   | 14        | 122         | 11              | 11          |

Table 1. Location of the reported AIS position on the vessel.
Having established a common set of approach trajectories, the speed-over-ground variable of each AIS-message is analysed with respect to the distance to the dock. Please note that as all AIS-messages with speed-over-ground reported to less than 0.3 knots are rejected. The distance from each AIS-message to the final position of each trajectory is calculated, and grouped into intervals of 0-10, 10-20, 20-30, 30-40, 40-50, 50-75 and 75-100 meters. The mean and standard deviation are calculated for the speed-over-ground and heading variable from the AIS-messages for each bin. The result can be seen in Figure 5, Figure 6 and Table 2.

**Figure 4.** Approach trajectories of MS Polarlys, MS Nordnorge and MS Trollfjord during 2019.

**Figure 5.** Speed over ground for the trajectories at various distances from the dock.
The trend for the heading during the approach is that the variance has more of a decline as the vessel approaches the dock compared to the speed-over-ground, converging to around 6 degrees at dock. The mean value and standard deviations shown in Table 2.

| Interval  | Speed-over-ground (knots / m/s) | Heading (deg) |
|-----------|---------------------------------|---------------|
|           | Mean (knots / m/s) | Std. dev. (knots / m/s) | Mean (deg) | Std. dev (deg) |
| 0-10m     | 0.61 / 0.31 | 0.22 / 0.11 | 5.55 | 1.21 |
| 10-20m    | 0.86 / 0.44 | 0.34 / 0.17 | 5.90 | 1.66 |
| 20-30m    | 1.05 / 0.54 | 0.40 / 0.21 | 6.13 | 2.53 |
| 30-40m    | 1.36 / 0.70 | 0.38 / 0.20 | 6.07 | 2.71 |
| 40-50m    | 1.62 / 0.83 | 0.34 / 0.17 | 7.03 | 2.92 |
| 50-75m    | 1.94 / 1.00 | 0.37 / 0.19 | 8.14 | 3.08 |
| 75-100m   | 2.22 / 1.14 | 0.39 / 0.20 | 8.64 | 3.89 |

Table 2. Summary of mean and standard deviation for speed over ground and heading for various distance intervals.
Analysis of anchored operation:
When vessel is moored, we assume that the positions are fixed, and corresponding position measurements and heading is sensor noise. The standard deviation for both vessels is similar, indicating that the majority of points are indeed from an actually moored vessel. The results are summarized in Table 3.

| Position and heading | MS Trollfjord | MS Nordnorge |
|----------------------|--------------|--------------|
| Latitude (m)         | 0.889        | 0.534        |
| Longitude (m)        | 0.832        | 0.497        |
| Heading (deg)        | 0.446        | 0.443        |

Table 3. Standard deviation for latitude, longitude and heading measurements while moored.

A typical plot showing the different accuracies are computed for selected points around the hull. The accuracy model is based on 1000 pseudorandom numbers drawn from the standard normal distribution function randn in MATLAB. As an example, position accuracies for different location around the hull is shown in Figure 7. For illustration, the heading accuracy (one sigma) is increased from 0.44 to 2.0 (deg) to see the effect of position uncertainties around the hull. Position accuracies on latitude and longitude are unchanged for MS Nordnorge which is used in the further study.

Figure 7. Computed position accuracy as points for different locations around the hull (MS Nordnorge). Both axes in meters. Notice, the heading standard deviation is exaggerated to illustrate the effect of varying position accuracy around the hull. Axes in meters.

The GNSS receiver is located as position (0,0) and the analysis is based on the aft port point (-76, -8). All coastal ferries are docking alongside with port side to the quay.
3. Closed-loop analysis of automatic docking
To propose new requirements for PVT used for autodocking, a simple mathematical model describing the closed-loop dynamics can be used.

In low speed operation, surge, sway and yaw motion of a ship can be modelled as 3 individual linear mass-damper-spring systems, see Figure 8. Surge motion are coupled with heave and pitch motion, but for the sake of simplicity, the heave and pitch motion are not considered for the analysis. Sway and yaw are coupled dynamics, but in this simple analysis we further assume that the motions are decoupled. Detailed information on mathematical modelling of ship’s motion can be found in Fossen [4].

![Figure 8. Linear mass-damper-spring system.](image)

Introducing a simple PD control law by:

\[ f = -K_d \dot{x} - K_p x \]

yields the closed-loop dynamics described by the following mass-damper-spring model. \( K_p \) and \( K_d \) are controller gains for the PD controller. Notice, that for surge, sway and yaw motion there is no natural restoring/spring force (\( k=0 \)).

\[ m \ddot{x} + (d + K_d) \dot{x} + K_p x = 0 \]

where

\[ 2\zeta \omega_n = \frac{d + K_d}{m} \]

and

\[ \omega_n = \sqrt{\frac{K_p}{m}} \]

In closed-loop, \( K_p \) and \( K_d \) are both positive constants and the natural period \( T_n = \frac{2\pi}{\omega_n} \) satisfies

\[ 2\zeta \omega_n = 2\zeta \frac{2\pi}{T_n} = \frac{d + K_d}{m} = \frac{1}{T} + \frac{K_d}{m} \]

where \( d \) is the hydrodynamic damping coefficient, \( \omega_n \) is the natural frequency (undamped oscillator when \( d=0 \)) and \( \zeta \) is the relative damping ratio. In principle, the feedback from velocity will increase the
damping, whilst feedback from position will define the closed-loop bandwidth. Choice of controller gains must be based on feasible values due to the desired response needed and the effect of the "noisy" control signals to the propulsion system.

To obtain a **physical motion** accuracy of 0.1 meter as recommended by IMO, we have changed the noise model to fit the closed-loop requirement of 0.1 meter sideways and justified control gains to fit the desired closed-loop bandwidth requirement. Justified requirements are then:

\[
\begin{align*}
p &= 0.3 \text{ m (95\%)} \\
\nu &= 0.04 \text{ m/s (95\%)} \\
\psi &= 0.2 \text{ deg (95\%)} \\
\end{align*}
\]

**Figure 9.** Closed-loop response in sway at selected point. Position in [m], velocity in [m/s] and force in [tonnes].

**Figure 10.** Closed-loop response in surge at selected point. Position in [m], velocity in [m/s] and force in [tonnes].
Based on the simulation, the closed-loop control system will then have a sideways motion with an accuracy of 0.1 m (95%), whilst longship accuracy is 0.05 m (95%). The thrust needed for sideways control are relatively much higher compared to surge control because since heading noise will contribute "more" in longship direction than the sideways direction. The accuracy requirement for the heading sensor can be tightened to obtain less thrust usage of course. This study illustrate that the sensor configuration and sensor accuracies will be a trade-off of complexity, performance and cost for each vessel and selected operations. Shortly, the proposed methodology can be applied for different vessel and different type of operations as well. Due to scaling effect, a similar smaller or larger vessel can be scaled accordingly using Froude scaling.

4. **Integrity, continuity and availability requirements**

In addition to accuracy requirement, the integrity, continuity and availability requirements are also important with regards of safety. **Integrity risk** is the probability of providing a signal that is out of tolerance without warning the user in a given period of time. It defines the maximum probability with which a receiver is allowed to provide position failures not detected by the integrity monitoring system. The **continuity** of a system is the ability of the total system (comprising all elements necessary to maintain vessel's position within the defined area) to perform its function without interruption during the intended operation. The **availability** of a navigation system is the percentage of time that the services of the system are usable by the navigator. The dependencies of the requirements are shown in Figure 11.

Absolute safety cannot be achieved in any human or automatic control activity.

To justify the integrity requirements, which is highly connected to passenger's safety, we propose to justify the integrity requirements according to the effect of failure(s) during autonomous navigation. For example, the time to alarm (TTA) and alarm limit (AL) for example will depend on the actual requirement for the closed-loop control and the desired trajectory for the docking case. For the specific docking case, it is possible to define the desired trajectory to ensure a **safe speed** towards the dock if the control system fails. A separate fail-safe mechanism independent on the PVT solution can be implemented to avoid risk for the vessel or passengers.

For passenger safety, the probability concept can be used to define different safety levels as maximum horizontal acceleration values.

4.1. **Probability concept**

Based on the International Code on Safety for High-Speed Craft [5], we propose to use the probability concept to define maximum horizontal acceleration levels. If the actual velocity is below a safe limit, failure in position measurement will not cause any severe damage to vessel and thus reduce safety for passengers.

The probabilities quoted shall be on an hourly or per-journey basis, depending on which is more appropriate to the assessment in question.
| Probability             | Explanation                                                                 | Probability value |
|-------------------------|----------------------------------------------------------------------------|-------------------|
| Frequent                | Likely to occur often during the operational life of a particular vessel    | $10^3$            |
| Reasonably probable     | Unlikely to occur often, but may occur several times during the total operational life of a particular vessel. | $10^3$ to $10^5$  |
| Remote                  | Unlikely to occur to every vessel, but may occur to a few vessel of a type over the total operational life of a number of vessel of the same type. | $10^5$ to $10^7$  |
| Extremely remote        | Unlikely to occur when considering the total operational life of a number of vessels of the type, but nevertheless shall be considered as being possible. | $10^7$ to $10^9$  |
| Extremely improbable    | is one which is so extremely remote that it shall not be considered as possible to occur. | Less than $10^9$  |

Table 4. Probability, explanation with values, [5].

4.2. Safety levels
Safety level is a numerical value characterizing the relationship between vessel performance represented as horizontal single-amplitude acceleration (g) and the severity of acceleration-load effects on standing and sitting humans. The safety levels and the corresponding severity of effects on passengers and safety criteria for vessel performance is defined in Figure 12.

![Figure 12. Safety level with acceleration limits, [5].](image-url)
Based on the integrity risk probability requirement of $10^{-5}$, which is the limit of safety level 1 (minor) and safety level 2 (major), the maximum peak horizontal acceleration level should be less than $0.35g = 3.5 \text{ m/s}^2$.

**Notice**, if applying Froude scaling, the maximum acceleration level will be the same for different vessel types and operations.

### 4.3. Safety analysis

For the automatic docking case, we can assume that the vessel will be able to stop within 1 seconds, which is rather conservative. If we assume a continuity requirement of 5 sigmas for the velocity and uses the approach speed of 1 m/s for the distance 50-75 meter from the quay, the **maximum safe speed will be around 2 m/s** and corresponding g-force of 0.2 g horizontally. By using safety level 3 (hazardous and extremely remote) to define the acceptable integrity risk of $10^{-8}$ during docking phase (approximately 5 minute) it is possible to increase the alarm limit to 50 meter in this case. Time to alarm depends on the ships dynamics and must be chosen to small enough to give necessary response to reduce the speed below the safe speed limit. In our case, the time constant for this vessel is around 30 seconds, so alarm time less than 10 seconds will be sufficient time to make necessary correction in case of warning or alarm. Finally, we can propose the integrity requirements for this vessel's docking operation as:

- Alarm limit $\leq 50$ meter
- Time to alarm $\leq 10$ seconds
- Integrity risk $10^{-8}$ per 5 minutes
- Continuity 99.97% per 5 minutes

### 5. Conclusions

As seen from the study, the requirements for a feasible PVT sensor solution for autonomous operations depends highly on selected vessel and operation. The recommended performance values proposed by IMO for different operations must be adapted for autonomous operations and must include requirements for also heading and velocities. By using feedback control, it is necessary to include heading accuracy as additional requirements to calculate the vessel uncertainty zone describing the probability of the outer hull boundary. Different uncertainties covering both sensor noise, mounting error and error in the geometry model must be considered when computing the real physical location of selected points around the vessel. In addition, the feedback control system needs both position and velocity measurements to
obtain the necessary damping and desired response when approaching the dock. To reduce risk and effect of unwanted collision, it is possible to introduce the safe speed concept, which is maximum velocity the vessel can dock without significant degradation of safety. Based on the AIS analysis, it is possible to establish feasible safe trajectories for the docking operation and adjust the integrity risk and alarm limit accordingly. If the vessel speed is within safe limit during the docking phase, any failures due to navigational errors will be acceptable. To conclude, the final proposed requirements for the PVT navigational system are then proposed in Table 5.

| System level parameters | Service level parameters |
|-------------------------|--------------------------|
| Autonomic Operations    |                          |
| Horizontal (m)          | Accuracy (95%)           |
| Heading (deg)           | Integrity                |
| Linear velocity (m/s)   | Alarm limit (m)          |
| Time to alarm (sec)     | Integrity risk           |
|                         | Availability % per 30 days|
|                         | Continuity               |
|                         | Coverage                 |
|                         | Fixed interval (sec)     |
| Coastal                 |                          |
|                         | 10                       |
|                         | 1.0                      |
|                         | -                        |
|                         | 25                       |
|                         | <10                      |
|                         | 10^4                     |
|                         | 3 hours                  |
|                         | 99.8%                    |
|                         | 99.97%                   |
|                         | Global                   |
|                         | 2                       |
| Autodocking             |                          |
|                         | 0.3                      |
|                         | 0.2                      |
|                         | 0.04                     |
|                         | 50                       |
|                         | <10                      |
|                         | 10^8                     |
|                         | 5 min                    |
|                         | 99.8%                    |
|                         | 99.97%                   |
|                         | Local                    |
|                         | <1                       |

*Table 5. Justified PVT requirements for coastal and autodocking for the coastal express vessel.*

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