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Improved usability in DP tracking operations

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Abstract

This paper presents examples of improved usability in a low-speed waypoint tracking system. The improvements have partly been rendered possible by a path construction scheme where the type of path and speed profile provide complete path information. Combined with functionality, this ease the tracking operation and reduce operator's workload. Path construction, path properties and situations with several, maybe conflicting, assignments are presented and discussed. Usability examples of both functionality and the graphical user interface characteristic are provided.

Introduction

Waypoint tracking is a natural extension of the position and heading control modes of a dynamic positioning system. It controls the vessel along a track of predefined waypoints and the operator can usually choose between different heading and speed control modes. In low-speed mode (speeds up to 3-4 knots) waypoint tracking is an important component of advanced vessel operations such as cable and pipe laying, dredging, trenching, and surveying [2].

In the context of this paper, usability is part tracking functionality and part user interface characteristic. It has been a goal throughout the design process to focus on the user and much thought has been put into how different tools, such as path analysis and construction, can ease the operator's workload.

To achieve waypoint tracking while being able to incorporate vessel speed and acceleration and other dynamic constraints, analyze path properties in a straightforward manner, and facilitate an advanced interface implementation, new functionality has been developed: methods for path construction, speed profile generation, and tracking analysis tools. This paper will show usability examples rendered possible from the underlying functionality, GUI examples, and other elements that simplify often-used operations.

The background of this paper is the design, development and implementation of a low-speed waypoint tracking system. More specifically, we consider some of the important aspects of the reference model and the user interface. Most of the material is also applicable for high-speed waypoint tracking systems. The difference is mainly the number of controllable degrees-of-freedom (DOFs). In the underactuated case, it is impossible to control all DOFs directly. A vessel may be underactuated because of insufficient thruster arrangement or speeds that render the tunnel thrusters ineffective. For instance, a platform supply vessel at zero or low speed is typically overactuated and controllable in surge, sway and yaw. However, at high speeds the sway motion can only be controlled indirectly so the system is said to be underactuated.
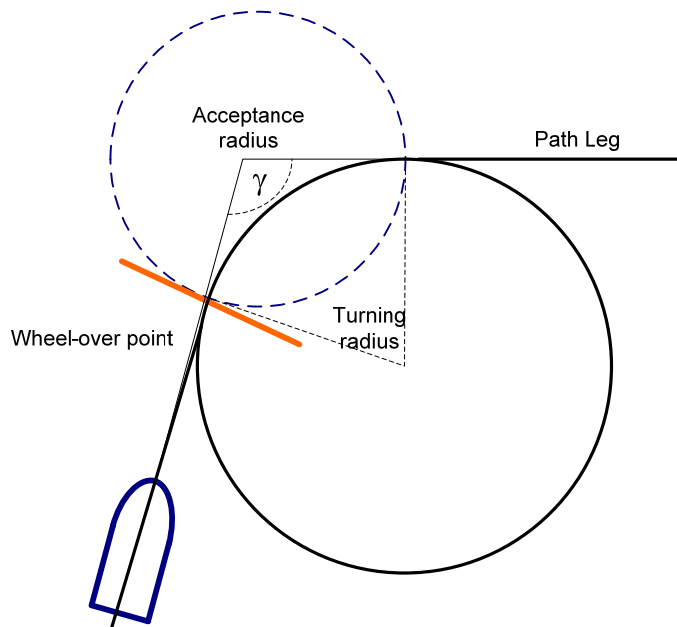
From points to paths

Waypoint tracking is an essential part of the reference module in the DP control system. It must provide continuous reference signals for position and velocity to maneuver the vessel from waypoint to waypoint.

A waypoint consists of at least a position (e.g., latitude and longitude, UTM, etc.), and perhaps a turning radius, speed and heading setpoint. For a DP tracking system, the waypoints usually comes from an external source.

The radius of a waypoint's acceptance circle, where the vessel starts turning towards the next waypoint is related to the turning radius

$$r_{turning} = r_{acceptance} \tan\left(\frac{\gamma}{2}\right)$$

where γ is the angle between previous and next waypoint.
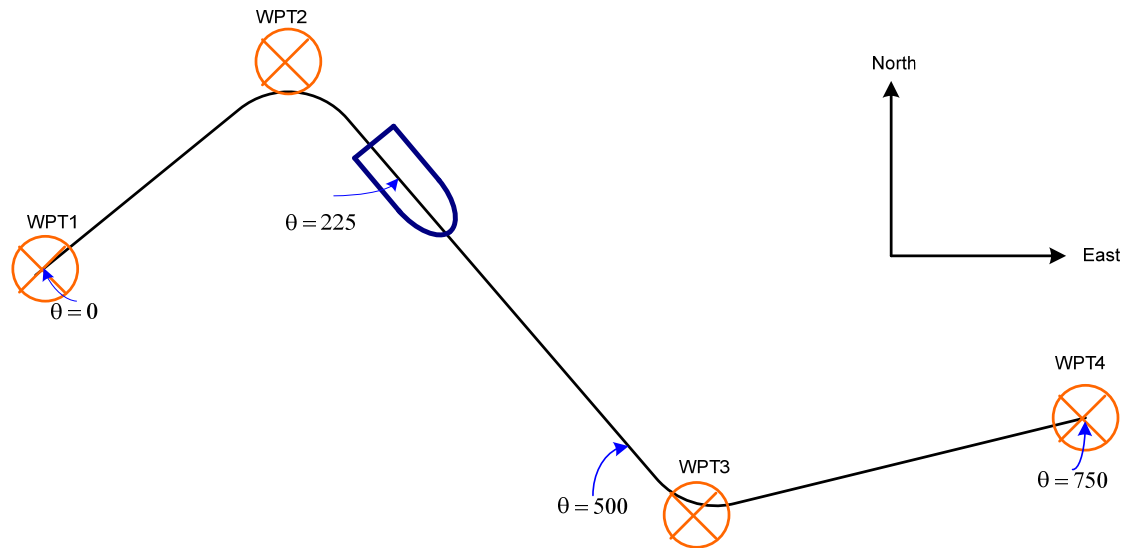

Waypoint with acceptance and turning radius

The goal for the DP control system is to convert the waypoints into a path that can be followed by the vessel. The classical approach is to connect the waypoints using straight lines and inscribed circles determined by the turning radius. There exists a number of different ways to construct a path from a set of points, e.g. different interpolation techniques and optimization (shortest route through a set of points, design for minimum time and energy, add vessel speed and acceleration constraints). See for instance [1], [3] and [4.].

One of the most important aspects is that the reference signals to the control module is smooth. If the constructed path is discontinuous, it must be smoothed in some way before the reference signal enters the control loop. By initially creating a smooth path, we avoid introducing additional complexity at a later stage.

We consider a parameterized path p parameterized by θ

$$p(\theta) = \begin{bmatrix} North(\theta) \\ East(\theta) \end{bmatrix}$$

Theta is denoted as the path parameter and $p(\theta)$ gives the position according to theta in an Earth-fixed reference frame

WPT2

North

WPT1

$\theta = 225$

East

$\theta = 0$

WPT4

$\theta = 750$

WPT3

$\theta = 500$

A set of waypoints and a path parameterized by length.

We will later show how such a path can be obtained from a set of waypoints, but we will first discuss the motivation for using parameterized paths. For a thorough examination of parameterized paths in reference models, see [5].

The parameterized path and its derivatives contain all information about the path's geometric properties: position, tangent, tangential path heading, curvature, etc. Assume the path constructed from the waypoints is given as

$$p(\theta) = \begin{bmatrix} North(\theta) \\ East(\theta) \end{bmatrix} = \begin{bmatrix} x(\theta) \\ y(\theta) \end{bmatrix}, \quad [m]$$

We use the following short-hand notations to define the path derivatives.

$$p^s := \frac{d}{d\theta} p(\theta) = \begin{bmatrix} x^s(\theta) \\ y^s(\theta) \end{bmatrix}, \quad [m/s]$$

$$p^{ss} := \frac{d^2}{d\theta^2} p(\theta) = \begin{bmatrix} x^{ss}(\theta) \\ y^{ss}(\theta) \end{bmatrix}, \quad [m/s^2]$$

$$p^{sss} := \frac{d^3}{d\theta^3} p(\theta) = \begin{bmatrix} x^{sss}(\theta) \\ y^{sss}(\theta) \end{bmatrix}, \quad [m/s^3]$$

and find the path heading, curvature and change of curvature from the path derivatives

$$t = \tan^{-1}\left(\frac{y'}{x'}\right), \quad [rad]$$

$$c = \frac{x'y'' - x''y'}{\left((x')^2 + (y')^2\right)^{\frac{3}{2}}}, \quad [rad/m]$$

$$\dot{c} = \frac{x'y''' - x'''y' - 2c\left(x'x'' + y'y''\right)}{\left((x')^2 + (y')^2\right)^{\frac{3}{2}}}, \quad [rad/s]$$

The parameterized path consists of smaller path segments and is constructed as follows

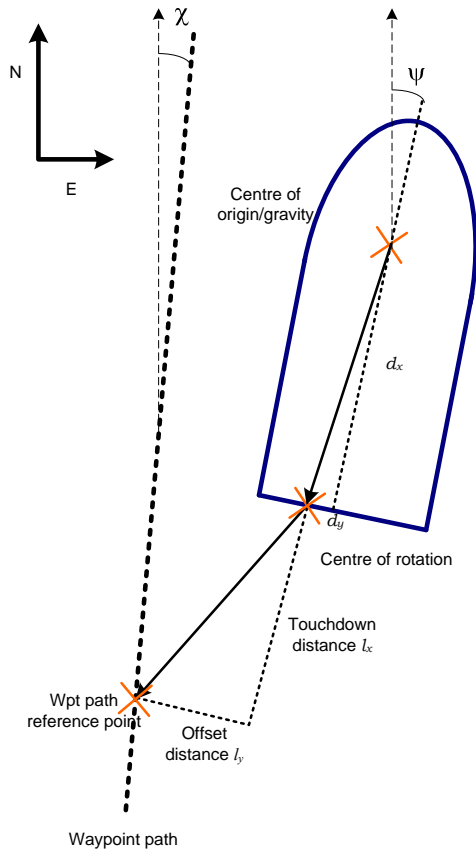|	Path Construction Algorithm
1	Find suitable path segment endpoints based on a list of waypoint locations and acceptance radius
2	Determine endpoint derivatives. Smoothness of the entire path follows by using similar endpoint values for path segments before and after endpoint.
3	Find polynomial representation for path segment using a proper path parameterization length.

The advantage with this path representation is that we are able to specify complicated paths composed of a number of simple motions since initial position and curvature can easily be matched with the previous segment's position and curvature.

In many applications, the primary goal is for a reference point outside the vessel to follow a path. This can e.g. be a plough or pipe section on the seabed. To account for this, we use a vector l with distance from vessel's centre of gravity to reference point, and then compute a path for the vessel centre of origin/gravity (CO). When centre of origin is equal to the centre of rotation (CR), we find the CR path as follows:

$$p_{CR}(s) = p(s) + R(\chi)\begin{bmatrix} l_x \\ l_y \end{bmatrix} \quad \text{where} \quad R(x) = \begin{bmatrix} \cos x & -\sin x \\ \sin x & \cos x \end{bmatrix},$$

χ is the tangential path heading, and l_x and l_y is the longitudinal and lateral offset. $R(x)$ is a rotation matrix. The longitudinal offset l_x is often referred to as the touchdown distance since this would be where a e.g. a cable touches the sea bottom. The derivative of the rotation matrix is

$$\dot{R}(\chi) = R(\chi)S(r), \quad S(r) = \begin{bmatrix} 0 & -r \\ r & 0 \end{bmatrix}$$

Vectors between centre of gravity, centre of rotation and desired path location

The CR path derivates are

$$p'_{CR}(\theta) = p'(\theta) = R(\psi_c)$$

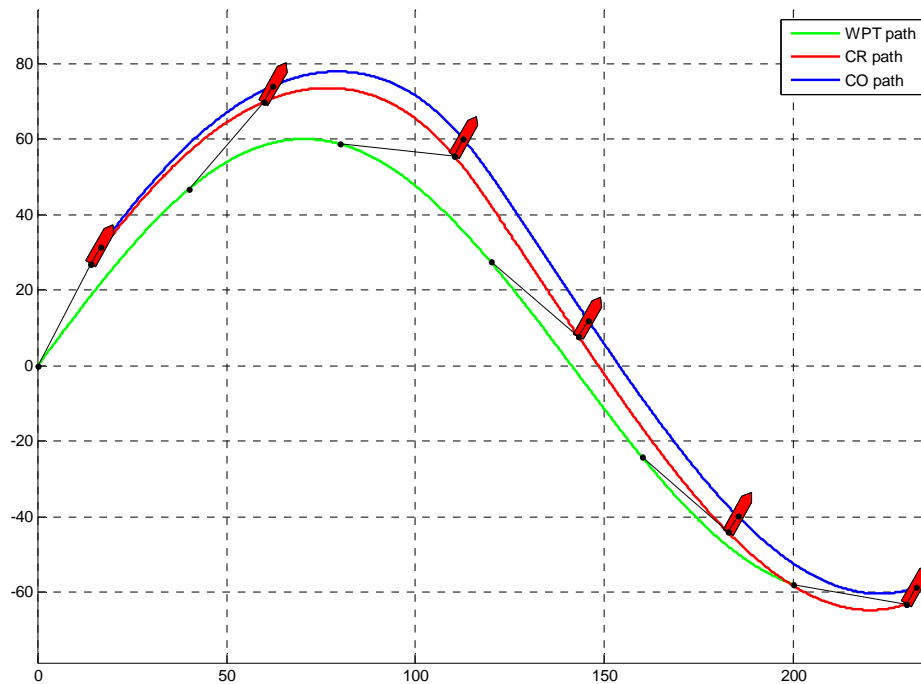$$p''_{CR}(\theta) = p''(\theta) - R(\psi_c)^2 - R(\psi_c)$$

In a similar manner, we find the path and path derivatives for the centre of origin when it differs from the centre of rotation by using a vector d with distance between CR and CO in the vessel-fixed reference frame:

$$p_{CO}(\theta) = p_{CR}(\theta) - R(\psi)\begin{bmatrix} d_x \\ d_y \end{bmatrix}$$

where ψ is the vessel heading. We find the CO path derivatives by substituting the curvature c with vessel's rate of turn.

The figure shows the three different paths and a vessel with fixed heading to better illustrate the effect of vectors between the different paths

By replacing the derivatives for the waypoint path $p(\theta)$ with derivatives for the CR and CO path, we are able compute similar path information (tangent, curvature etc.) for both the CR and CO path.
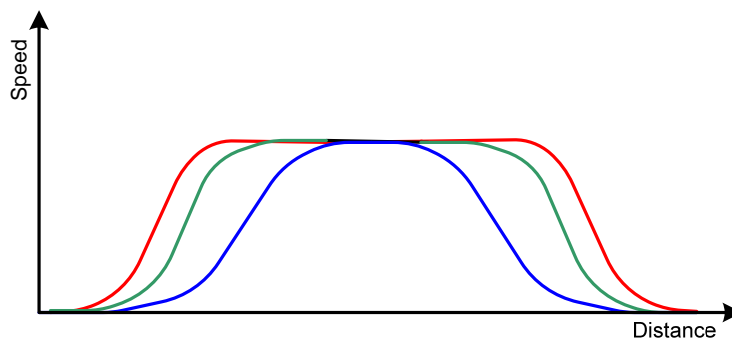
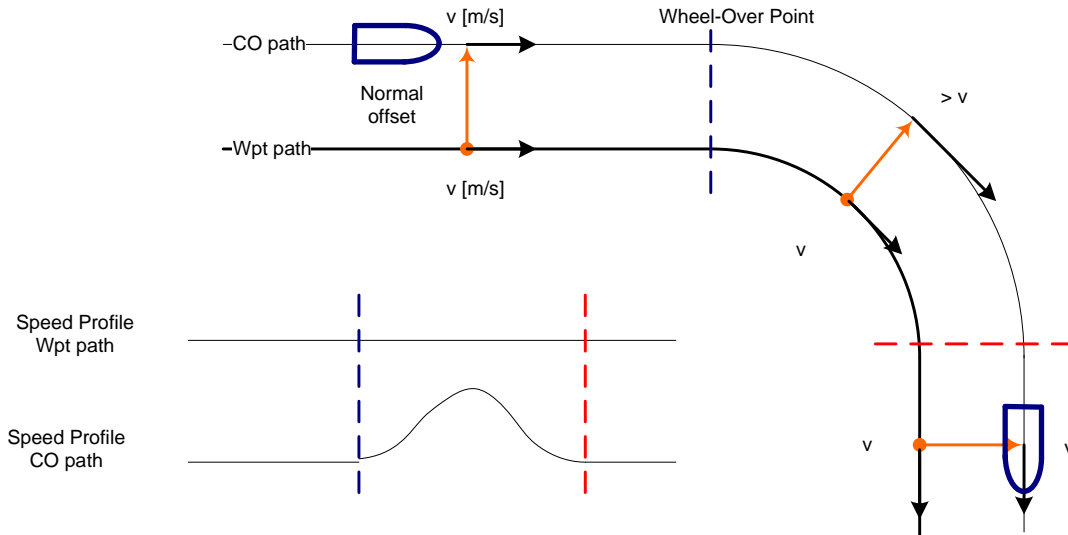**The waypoint path (green), CR path (red), and CO path (blue).**

Path Speed Profile

We have now found the path that the vessel shall follow, but have yet to decide the progress along the path. A tracking task nearly always involves some sort of dynamic behavior along the path: usually, a time, speed or acceleration assignment must be met. The dynamic assignment may be automatically generated, supplied with the waypoints, or may come from an operator. Some examples of such assignments are:

- keep constant speed along path,
- maintain a steady speed for a certain time period,
- be at a certain waypoint at a certain time,
- complete track at minimum time without violating operation constraints, and
- use a specified force for acceleration/braking

Speed profiles based on different dynamic objectives: Red curve: minimum time, blue: minimum force.

We generate a path speed profile with a speed assignment as a function of covered path distance. This is the speed to be kept on the waypoint path. The corresponding speed on the CR and CO path is computed from the path derivatives. Consider the next figure: to maintain a given speed on the original waypoint path the vessel must go faster during turns due to a smaller path tangent value.

Speed profiles on WPT and CO path with an offset normal to the path direction

The information about the waypoint, CR and CO path and their derivatives let us:
- Know properties of paths for centre of rotation, centre of gravity and waypoint table.
- Verify path construction
- Check that chosen offset is ok (depending on track construction strategy)

When we combine the path information with the speed profile we have more versatile tools available that enable us to:
- find speed and acceleration values on all path segments
- analyze path speed profile (certain speed/acceleration values) against limiting factors for entire waypoint, CR, and CO path.
- detect potential conflicts between simultaneous operations, e.g., heading change during a turn and keeping maximum speed on track
- calculate new speed setpoints to eliminate conflicts

Factors that limit speed assignment include, but are not limited to, vessel speed in turns, rotation during heading change, vessel speed/acceleration/rate limits, and dynamic limits for the reference point along the waypoint path.

Solutions are found analytically and are thus available instantly, eliminating the need for algorithms that involve searching and trial-and-error.

Example: Maximum path speed vs. heading change operation and vessel speed limits
To demonstrate the proposed method we'll consider a vessel in a heading change operation – 270 degrees clockwise (for presentation purposes) – during a 90-degree turn. The operation is illustrated in the figure below.

The objectives in this operation are:
1. We want the waypoint (which, in this case coincides with CR path) to be followed with a certain speed
2. The corresponding CO path speed shall stay below vessel speed limits
3. The heading rate-of-turn (ROT) must be large enough to finish heading operation.

These objectives may conflict, but knowing the CR and CO path derivatives, the vessel speed limits in CO and heading ROT we are able to compromise on a the maximum CR path speed that satisfies objective 2 and 3.
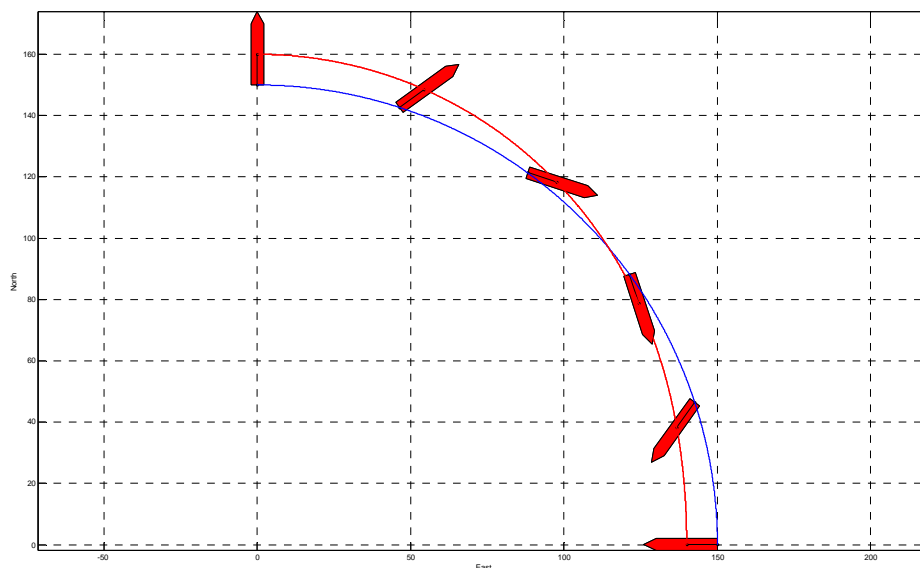
We consider the first two objectives: The speed limits are given as surge and sway values in the vessel frame. We therefore convert the CR speed to the vessel frame. Given a CR path speed assignment and path geometry, the inertial speed in CO is

$$V_{CO} = \dot{p}_{CO} V_{CR}$$

We then have that

$$V_{CO}^{\text{vessel}} = R^{\times}(\psi) V_{CO} = R^{\times}(\psi) \dot{p}_{CO} V_{CR}$$

Using this identity, we are able to check whether a speed assignment V_{cr} exceeds the vessel speed limits, and by calculating backwards, use the speed limits to find the maximum speed assignment.

The path for the centre of rotation is shown in blue, and the path for the centre of gravity is red. Different vessel snapshots show the operation progress.

Path parameter update law

We have now generated the path and found a feasible speed profile along it. We next look at the update law for the reference model. The update law's task is to send reference signals to the numerical control law such that the vessel moves according to desired path and speed.

The path parameter θ is the precise reference position on a path segment, and by constructing an update law for θ we control the progress along the path.

A straight-forward solution to advance the reference model along the generated path would be

$$\dot{\theta} = v_p(\theta)$$

where v_p is the path speed at the current location. This will ensure that the reference model follows the path speed profile and sends out matching position and velocity reference signals to the controller.

However, to make sure that reference position and speed stay close to the vessel position and speed we implement the path parameter update law with mechanisms that correct the path parameter progress given the error e between vessel and reference model position:

$$\dot{\theta} = f(v_p(\theta), e)$$

Deviations between vessel and reference model occur because of unmodeled disturbances etc. and e provides vessel feedback to the reference model. When there is zero deviation, the path parameter follows the path according to v_p(theta) and, otherwise, rapidly catches up with the vessel position.

Operator Interaction

This section will give an overview of the user interface, discuss items that we think improves usability and show examples of how the theory from the previous section is applied.

The user interface for waypoint tracking is implemented in the existing DP system and adopts the existing graphics scheme. New graphic symbols must also match the existing to ensure a familiar experience. However, since a tracking operation differs from a change position operation, we have chosen to make parts of the user interface and input device operation specific. That is, after a tracking operation has started, the graphical user interface will emphasize information that is essential for tracking. The input device also adapts to the situation with new commands replacing those that no longer apply in a tracking situation.

When an operator has the freedom to enter and manipulate e.g. waypoint data, probably situations will arise where you get unexpected results, such as strange path shapes, conflicting speed and heading setpoints etc. Restricting the operator's possibilities reduces the chances of unexpected situations, but affects user experience and may feel conservative. The tracking user interface's goal is to give the operator as much freedom of choice as possible and preparing for potential operator blunders by:

1. Minimize chance of mistakes occurring
2. Minimize impact if mistakes occur

Errors can, and will, be made. Hints, instant and visual feedback on errors can show the user what went wrong and why the situation occurred. The goal is to both minimize impact and explain and educate the user such that errors can be avoided in the future.

A waypoint tracking operation starts by loading the waypoints into the waypoint table. From here you can make changes to values for each specific waypoint. You can also save and load a track from and to a file, rename your track or load a new track from a chart system.

Whenever a change has been made to a waypoint, a yellow marker will appear in the "Applied" column. If the change made resulted in an invalid track, the marker will be red. Path analysis methods and choice of path construction strategy determine the track validity. Changes are approved by pressing the "Apply" button.

The waypoint path is constructed from the waypoints and shown on the 3D scene as a yellow path. It represents the predicted path of the vessel centre of rotation. After the operator has activated the tracking operation, the waypoint track is shown as a grey highway. The green box, located at the centre of the vessel, visualizes the cross track error limits.
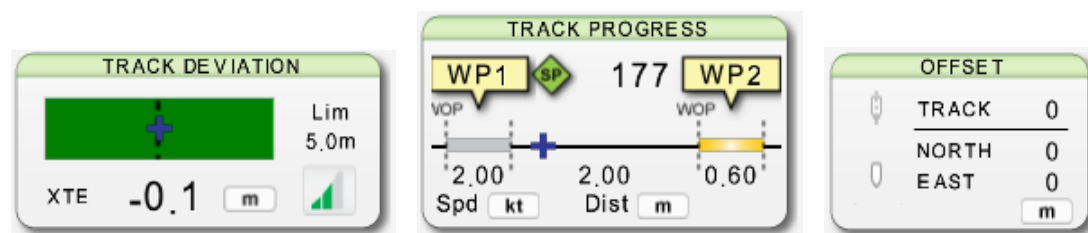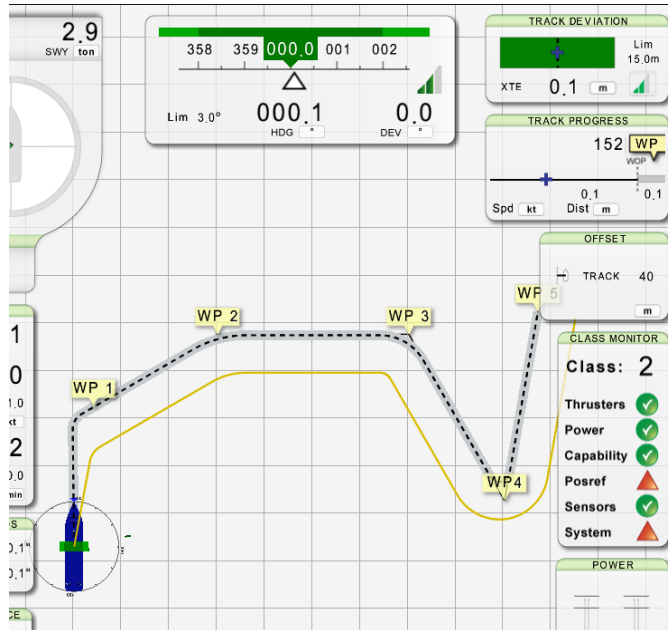

Waypoint table

Note that the head's-up-displays (HUDs) change after the tracking operation has started. The HUDs supply the user with what we have identified as key knowledge for the current operation. During a tracking operation the user sees information about track progress, speed setpoints in turns and on straight line segments, track deviation and chosen offset values.
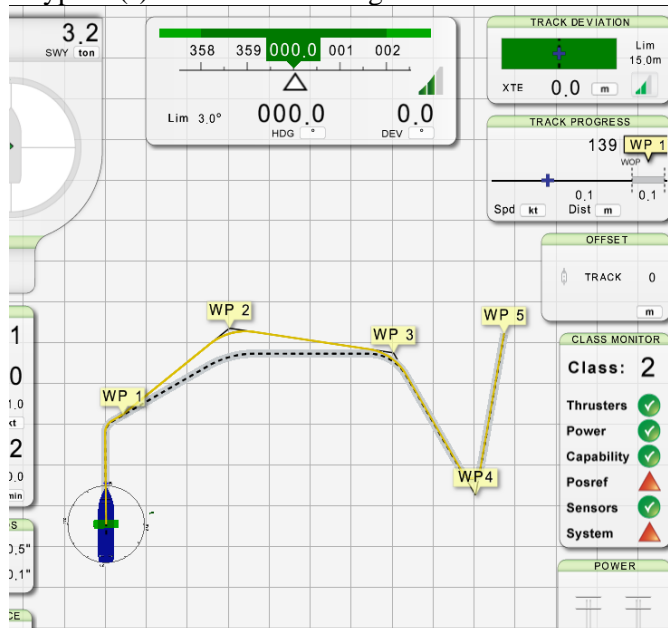

For a constant speed profile, the reference speed in turns may vary from straight line segments due to path curvature, heading change operations and vessel speed limitations. The maximum allowable speed through a turn is calculated in a similar manner to the example in the previous section.

We aim to incorporate a what-you-see-is-what-you-get principle in the user interface. Changes to the waypoint geometry or offset vector are shown instantly as a yellow edit curve on the 3D scene and provides visual feedback. During tracking operations, the transition from the current highway to the new edit curve is always shown. The shape depends on the current along-path speed and the selected speed towards the offset track (perpendicular to the track direction). After applying the changes the yellow edit path becomes the new highway to be followed.
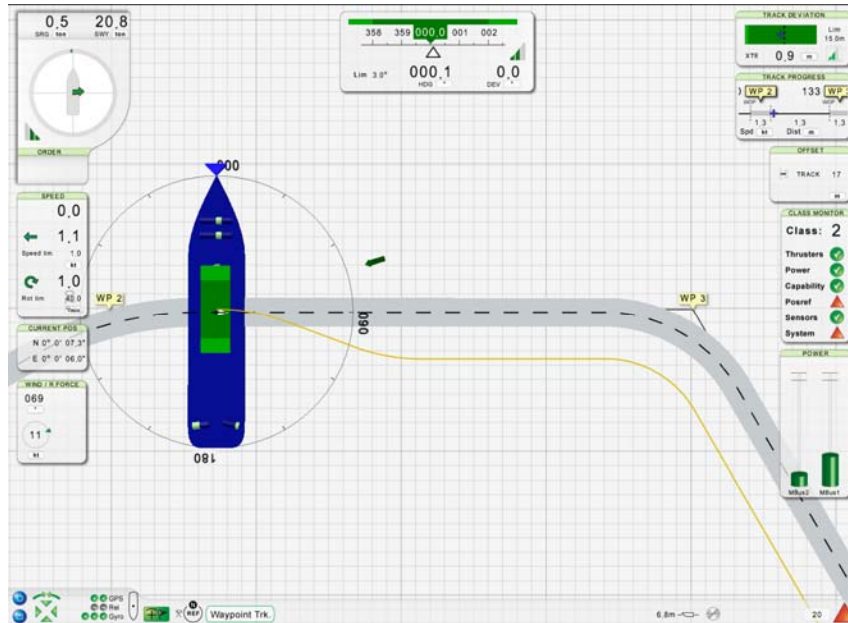

Path with new offset

Path analysis from the previous section makes it easy to quickly analyze changes to the path, speed profile and other operational changes. If the operator makes changes that cause an invalid path (e.g., two waypoints are too close, new offset value is too large), the edit path will be shown in red and it will be impossible to apply the changes. In addition, the waypoint(s) with invalid settings will be marked in the waypoint table.
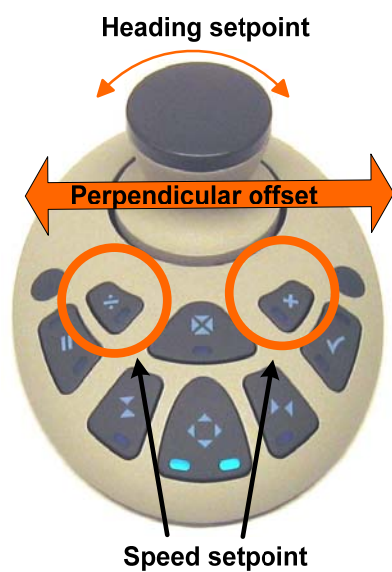

Path with moved waypoint

Transition from current to new path

Most changes and commands are performed in the Tracking Operation pane. However, three settings, manipulating the perpendicular offset distance and adjusting the speed and heading setpoint, are also available from the input device during low-speed tracking operations. Interviews with DP operators identified these as the most used commands and making them more accessible lightens the DP operators work load.

Some situations must of course be handled manually. The way-point tracking will go into a fault state if one of the following conditions occurs:

1. All position reference systems lost (causes dead reckoning).
2. All heading sensors lost, (will also cause dead reckoning).
3. No thruster forces in surge, sway or yaw.

When going into the fault state the controller will try to stop the vessel: speed set points are set to zero and when model estimated speed has reached zero, the controller will try to keep the estimated position.

When thruster forces are available in 3 DOF and position reference systems and heading sensors are OK the system leaves the fault state. If the vessel has drifted of more than 3 meter from last known position on track (or more than 3 degrees), a dialog box will pop up with two selections, continue or exit tracking. The yellow curve will appear and show the route back to track. The operator must then decide what to do next.

Conclusion

We have seen how to construct a parameterized path from a set of waypoints and how to apply it in the reference model of a low-speed waypoint tracking system. The path provided information about position, path tangent, curvature, and in combination with a speed profile, we determine speed and acceleration values for the entire path. All these values can also be found for the path described by the centre of rotation and centre of gravity. Various usages of this information to improve usability were discussed. Parts of the user interface were presented: operation specific information available when tracking operation starts, fast path analysis, visual feedback on path geometry and setpoints. When combined, these elements reduce operator workload during waypoint tracking operations.

References

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