SYSTEMATIC TECHNIQUES FOR FAIRWAY EVALUATION BASED ON SHIP MANOEUVRING SIMULATIONS

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SUMMARY

Ship Manoeuvring simulators are commonly used for training purposes. For research purposes the simulations can be human controlled on a full mission bridge simulator but the human interaction can be bypassed and the mathematical model of the simulator can be fed with different types of input. These different simulations types, *fast-time position captive*, *fast-time track captive, fast-time track predefined controls* and *fast-time track controller*, as well as *real-time simulation* are explained and the merits of each type are illustrated with an example of a deep-drafted and wide vessel on the Canal Ghent Terneuzen.

1 INTRODUCTION

Over the last decades ship sizes have increased dramatically for different types of vessels (including container ships and LNG-carriers). Fairways often have not increased at the same rate. As a result, larger ships may now sail in areas that were originally designed for smaller vessels. In some cases new infrastructures, especially locks, make it possible for larger ships to get access to an existing canal which might lead to problems when the bathymetry of the canal is kept status-quo. The Knowledge Centre Manoeuvring in Shallow and Confined Water (www.shallowwater.be), which is a collaboration between Flanders Hydraulics Research (FHR) and the Maritime Technology Division of Ghent University, wishes to share their experience in evaluating and investigating possible bottlenecks in such situations. This paper presents some methodologies that are used to evaluate manoeuvres in shallow or confined water based upon simulation techniques.

Systematic investigation of ship manoeuvring in shallow and confined water is performed by Flanders Hydraulics Research (FHR) and Ghent University (UGent) through five different simulation techniques. Each of these techniques essentially relies on the same mathematical manoeuvring models which are nowadays available for a large range of sea-going and inland vessels at different loading conditions and under keel clearances (or water depth to draft ratio). Most ships in the simulator fleet have in-house developed modular mathematical models of the tabular type (Delefortrie *et al.*, 2016). New developments, updates, improvements and extensions are based upon research carried out in the Towing Tank for Manoeuvres in Confined Water (co-operation Flanders Hydraulics Research and Ghent University) or other test facilities available at FHR (lock access model, flumes, full-scale measurements).

In principle, the core of a mathematical model is a set of differential equations, i.e. the equations of motion of the ship, which express the equilibrium between inertial forces and moments on one hand and all internally and externally generated forces and moments acting on the ship on the other. The latter can be subdivided in hydrodynamic reaction forces and moments on the hull due to the ship's accelerations and velocity components through the water, the forces and moments induced by the ship's propulsion system and controllers (rudders, thrusters, …), hydrodynamic forces induced by the vicinity

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of the lateral boundaries of the navigation area (bank effects) and due to the interaction with other ships (ship-ship interaction), forces and moments caused by waves, forces exerted by tugs, anchors, mooring lines, winches, contact with fenders and structures, and finally aerodynamic forces due to wind. It should be emphasized that all forces and moments of hydrodynamic origin are, moreover, significantly dependent on the water depth. This list is not exhaustive.

The number of differential equations of a mathematical manoeuvring model, i.e. the number of degrees of freedom (DOF), is minimum three (the horizontal degrees of freedom: surge, sway, yaw), often four (including roll) and maximum six (including the vertical motions: heave and pitch). The mathematical models used at FHR cover all six degrees of freedom, the models discussed in this paper will be mainly restricted to the three horizontal degrees of freedom. In case a 3 DOF or 4 DOF approach is used, the vertical degrees of freedom may be covered by a separate mathematical model which calculates the vertical motions, which are dominated by squat (sinkage and trim) in absence of waves.

Essentially, the following input is required to calculate the forces and moments formulated in the mathematical model:

- the ship's position (absolute, and relative to the horizontal and vertical boundaries of the navigation area), in all considered degrees of freedom;
- the ship's velocity components (over ground and through water);
- the ship's acceleration components (over ground and through water);
- the propulsion settings (e.g. propeller rate of revolution, pitch setting, …);
- the control settings (e.g. rudder angle, rate of revolution of bow/stern thrusters, …);
- the wave climate;
- the wind field;
- parameters w.r.t. other external forces (tugs, lines, …).

It should be mentioned that throughout this paper the term "position" is used for determining both the coordinates of the origin of a ship-bound coordinate system with respect to an earth-bound coordinate system, and the angular rotations between both systems. Therefore, the heading angle of a ship is included in the term "position". Similarly, "velocity components" and "acceleration components" refer to both linear and rotative components; e.g. a ship's rate of turn is also considered to be a velocity component. For a 3 DOF mathematical model, the position is given by (x_0, y_0, ψ), velocity by (u, v, r) and accelerations by $(\dot{u}, \dot{v}, \dot{r})$.

Among the different simulation techniques which will be discussed, a first distinction can be made between real-time and fast-time techniques. The authors are aware of the fact that these terms might have another meaning in a different domain of engineering sciences. In ship manoeuvring simulation, the term "real-time" means that the duration of a virtual, simulated event is equal to the duration the event would take in the real world, so that the real and simulated time scales are equal. This is typically a requirement if the input of the controls of the ship (rudder deflection, propeller rate, tug assistance, bow or stern thrusters) is given by a human (captain, wheelman, pilot, skipper), based on visual observations.

If there is no need for the simulation to take as long as it would take in reality, the simulation can be speeded up. The time needed for such a simulation is determined by the computing time required to run the calculations. Since the duration of the calculation/simulation is usually (much) shorter than real-time, these types of simulation are referred to as "fast-time" simulations (or, alternatively, simulations without human interaction). Four types of fast-time simulation will be discussed, each type having its own merits and disadvantages, whilst only one type of real-time simulation is considered. All five types will be described and discussed in Section 2, and applied to a bulk carrier sailing southbound on the Canal Ghent-Terneuzen, connecting the port of Ghent (Belgium) with the lock system in Terneuzen (the Netherlands) which gives access to the Western Scheldt and to the North Sea.

2 SIMULATION TYPES

In this section, four types of fast-time (FT) simulations will be considered: *fast-time position captive*, *fast-time track captive, fast-time track predefined controls* and *fast-time track controller*, as well as *real-time simulation*, involving human control. The distinction between the different types depends on the following characteristics:

- Real-time or fast-time;
- Predefined or free trajectory (captive or free-running);
- Predefined control settings; automated track control or human interference;
- Time dependent or independent output (steady or non-steady);
- Force output or trajectory output.

2.1 Fast-time Position Captive

The FT Position Captive type of simulation is the simplest of the four types of fast-time simulation. The mathematical model is used in a steady mode, which means accelerations are zero so their effect is not accounted for. The mathematical model calculates the forces and moments based on constant input values for the position (x_0, y_0, ψ), velocity components (u, v, r), propulsion settings, control settings, environmental (wind, waves, current) and external parameters. Due to the steady character, there is no time dependency (Table 1).

Due to the forced character of the simulation run, there is in general no equilibrium between the forces and moments acting on the ship and the external forces (Figure 1); therefore, the sum of forces and moments is expected to be non-zero. These forces and moments are available for further analysis as a function of the input parameters. Besides horizontal forces and moments, a similar approach can be followed for calculating vertical motions due to squat in case a separate mathematical model for vertical motions is available.

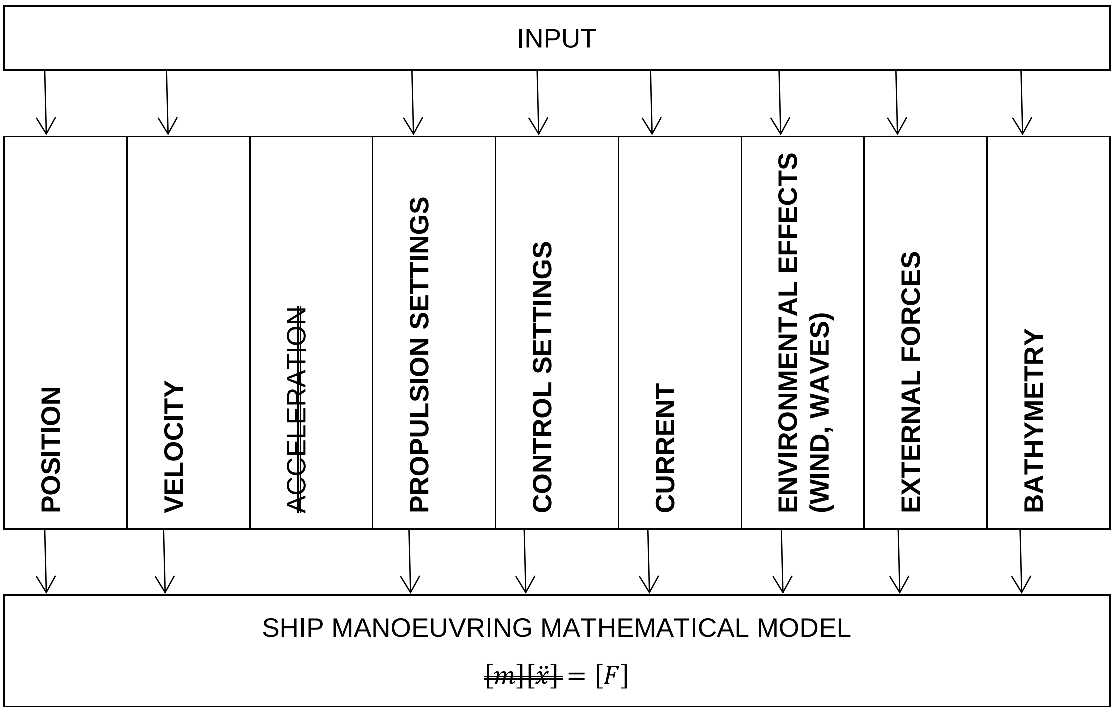


Figure 1 Calculation scheme of Fast-time Position Captive

This type of simulation can be used for investigating the effect of systematic parameter variations. As a first (simple) example, this type can be used to calculate the residing forces acting on a ship for a range of combinations of forward speed and propeller rates, which leads to a self-propulsion curve (u, n) of a ship at different water depths, at different lateral positions in a canal, etc. Similarly, the sensitivity of operational variables to parameter variations can be assessed.

Another application of this fast-time simulation is published in (Eloot, Verwilligen and Vantorre, 2007). A systematic study was carried out to determine the feasibility of a meeting manoeuvre between two Panamax vessels in the Culebra/Gaillard Cut, which is the narrowest section of the Panama Canal. It must be emphasized that the investigated situation is not up to date anymore, because in the meantime the Cut has been widened, deepened and straightened. The distance to the bank (or buoy line), the forward speed and three propeller rates were systematically calculated. The mathematical model provided a net yaw moment for each combination of forward speed, distance to the bank and propeller action. This yaw moment needs to be compensated by the rudder capacity, which can be obtained by re-running the simulations with maximum rudder deviation. As such the safety margin for the manoeuvre can be derived as plotted in Figure 2.

This technique can also be applied to assess which effort is required to keep a ship on a predefined steady track, and whether this effort can be realised by own controls or by means of tugs.

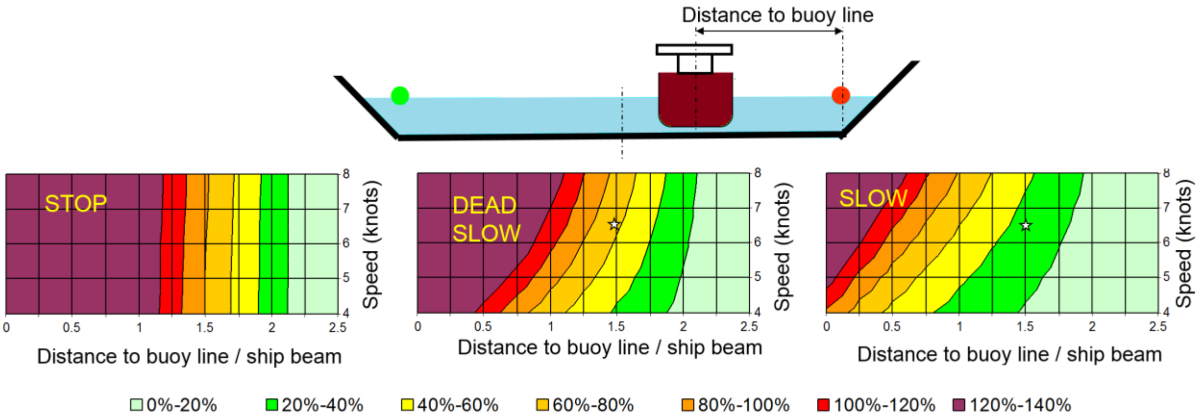


Figure 2 Required rudder capacity at different propeller rates and lateral positions from the buoy line

2.2 Fast-time Track Captive

The second type of fast-time simulation is very similar to the *FT Position Captive* but differs in the way it copes with accelerations. During the *FT Track Captive* simulations the vessel performs a predefined trajectory as a function of time by imposing the values for the horizontal acceleration components. At the starting time, the first calculation run uses the initial position and initial velocities from the input. The position of the next time step is only based upon the predefined accelerations. If the accelerations are all set to zero then the ship simply continues at the same speed in all directions (i.e. a rectilinear or circular trajectory, depending on the initial value for the rate of turn). As for *FT Track Captive* simulations, the trajectory of the vessel is prescribed, and local restrictions such as banks or other shipping traffic can be added to the simulation environment. The output of *FT Track Captive* simulations concerns time series of the net forces and moments that are computed by the mathematical model. Unlike *FT Position Captive* simulations, the forces originating from the ship's accelerations are taken into account during the calculations (Figure 3, Table 1).

One of the applications of this type of fast-time simulation is the comparison with full-scale measurements. During a full-scale measurement extra equipment is taken on board to measure the position of the ship with high accuracy (both in the horizontal as well as vertical directions) and to register the use of propeller and rudder. With these measurements the sailed track can be analysed and the accelerations (along all axes) derived from these accurate positions. This matrix with the accelerations $\dot{u}, \dot{v}, \dot{r}$, propulsion settings and control settings at every time step can be used as input for the *FT Track Captive* simulation. In this way, the full-scale measurement is replayed in the simulation. Since the position of the ship is directly linked to the input accelerations and not based on the forces and moments on the vessel, again there is no force (nor moment) equilibrium; as a result the output of the simulation run are time series of net forces and moments. The latter are of high interest for the validation of the mathematical model. In (Verwilligen *et al.*, 2015) a comparison is made between full-scale measurements on the inland vessel *MT Elise* and a *FT Track Captive* simulation.

Deviations between the original track and the simulated track may occur due to the accuracy of the integration of accelerations to positions.

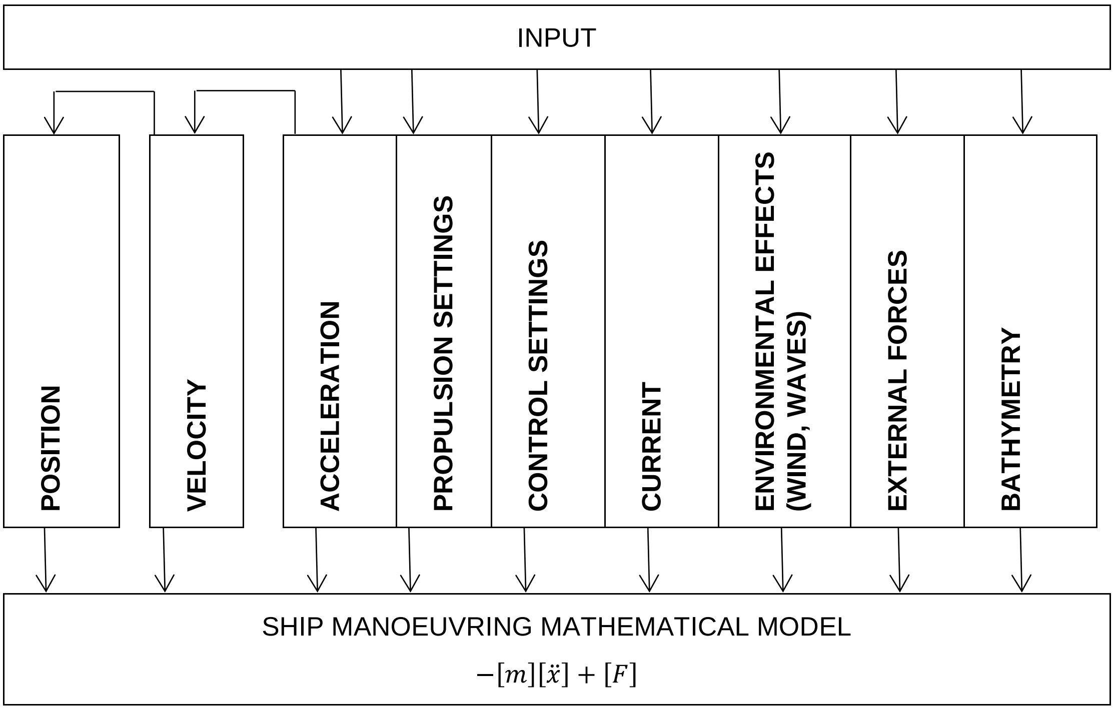


Figure 3 Calculation scheme of Fast-time Track Captive

2.3 Fast-time Track Predefined Controls

When applying the previously discussed simulation types, the equations of motions formulated in the mathematical model are not solved. This will be different for the simulation types described hereafter, where the mathematical model continuously solves a set of differential equations defining the manoeuvring behaviour of the ship. At every time step, typically 0.025 s, the forces and moments which act on the ship, are calculated; and superposed, and are transformed via Newton's second law into linear and rotative accelerations, which by integration lead to refreshed (linear and rotative) velocities and, finally, positions and directions.

The *FT Track Predefined Controls* method is therefore the first method with a total force equilibrium at every time step of the calculation (Table 1). In this type of simulation the net forces and moments are zero. As a consequence, the exact trajectory of the ship is only known after the simulation. The input for the simulation is, except for the initial time step t_0, the list of propeller rate, rudder deflection and tug assistance for every other time step. At every time step the mathematical model calculates all forces and moments, and with the superposition of all these forces and moments an acceleration (in all directions) is derived. Integration of these accelerations results in the velocity and position of next time step, so this is the first simulation type with a closed loop. In this type of simulation the simulated vessel sails freely in the environment. The simulation environment should not be laterally restricted, as one cannot predict the trajectory of the simulator vessel. Again, the force balance is respected at every time step throughout the simulation (Figure 4).

The most well-known example of *FT Track Predefined Controls* is the simulation of full-scale trials with a predefined procedure such as turning circle tests or crash stop tests.

In (Verwilligen *et al.*, 2015) the results of the full-scale measurement with the *MT Elise* are also used as input for this type of simulation. Instead of the derived accelerations, the full-scale measured rudder angle and propeller rate are used as input for the simulation. The output of the simulation is the followed trajectory (which deviates from the trajectory of the *MT Elise* because of differences between reality and simulation), speed and rate of turn. These outputs can be compared with the full-scale measurements and, when found satisfactory, details of the full-scale measurements can be investigated. For example the augmented resistance because of the high blockage as calculated in the mathematical model can be further investigated and conclusions can be drawn on the real trip based upon the *FT Track Predefined Controls* simulation.

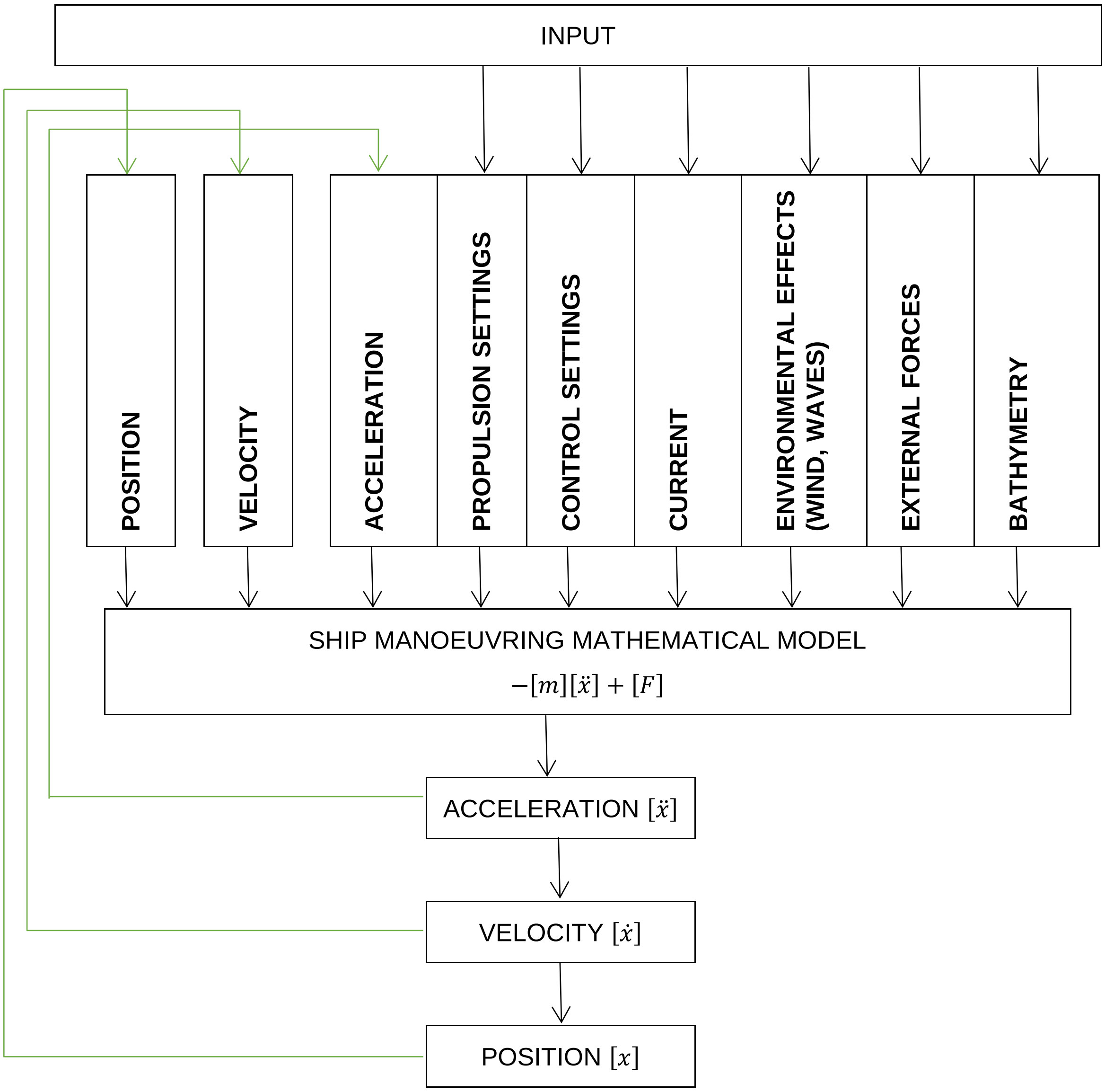


Figure 4 Calculation scheme of Fast-time Track Predefined Controls (closed loop in green)

The *FT Track Predefined Controls* results in a trajectory and manoeuvring behaviour which is more realistic because of the respected force balance but it is hard to duplicate an exact trajectory because the path of the vessel is unknown beforehand. Small deviations from the desired path on a narrow canal, for example, may result in excessive bank effects which then result in an unsuccessful simulation.

2.4 Fast-time Track Controller

This is the most advanced type of fast-time simulation. The simulation takes full use of the mathematical model and the controls of the ship (rudder and propeller) are changed in time through the Track Controller (Figure 5). This Track Controller is a type of simulated autopilot which steers the ship so it aims to follow a predefined path at a predefined speed. It uses a cost function with weight factors for different positions on the ship (e.g. at the bow, amidships and at the aft) so that the subsequent position (this is the feedback) of the ship which deviates least from the desired position is associated with the lowest cost. The number of positions that are considered in the calculations is also a setting. The input of this type of simulation is the desired trajectory and the settings of the Track Controller (Eloot, Verwilligen and Vantorre, 2009).

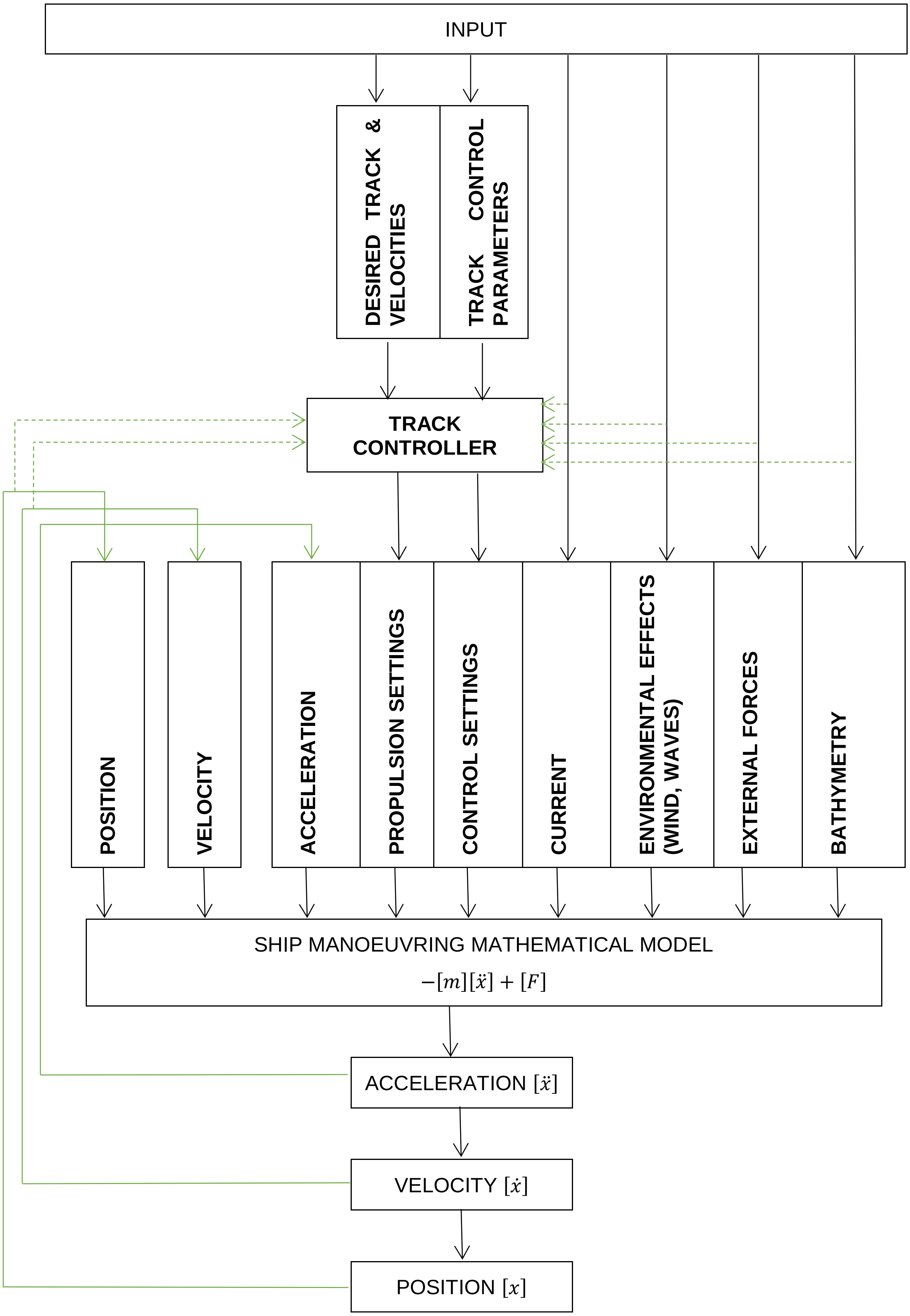
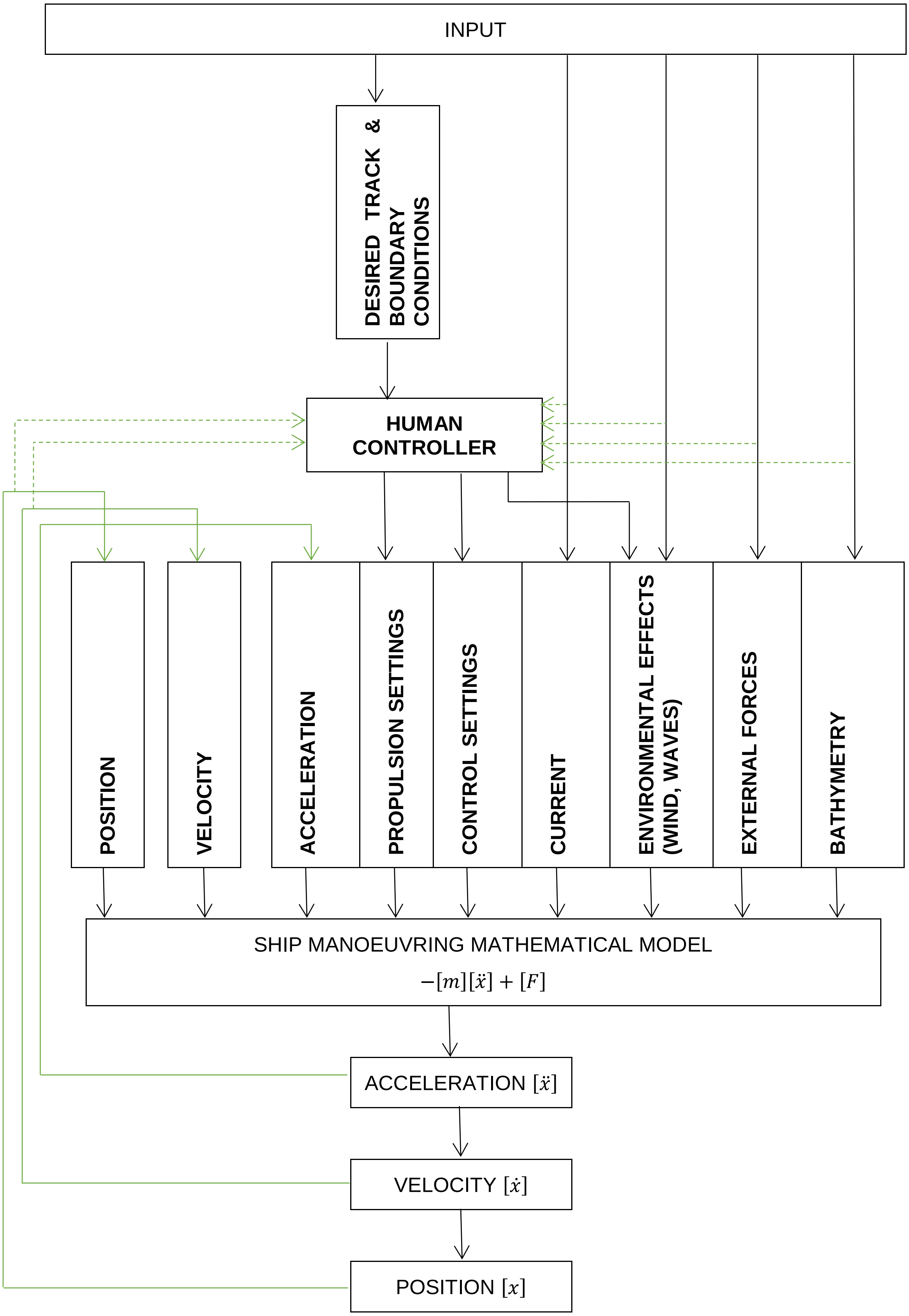


Figure 5 Calculation scheme of Fast-time Track Controller

3 REAL-TIME SIMULATION

In real-time simulations, the steering devices, like the engine's telegraph, rudder angles and thrusters, are controlled by a human person who also commands, if required, tug assistance (Figure 6). In other words, the actions of the person in charge of the simulations provide the only input for the mathematical model.



The advantage of real-time simulations is the completeness of the simulation technique by introducing the person (expert) in the loop. Obvious disadvantages of this tool are the relatively time consuming process for systematic investigation and the variability of the simulations, better known as the human factor during the simulations. Exact repeatability is not possible and the number of different set ups that can be tested for evaluation purposes is rather low, since only about 10 to 20 different simulation runs can be carried out per working day. The impact of the experience, skills and personal style of the seaman can have a significant impact on the results of the simulations.

Figure 6 Full mission bridge simulators 225 and 360+ at FHR

Real-time simulations can be used for the validation of the mathematical model. If a new manoeuvring model of ship is derived from model tests carried out in the towing tank then this manoeuvring model is tested by an experienced person familiar with the ship in real life. The same experienced person can also contribute to studies in which a new navigational situation is created. A limited amount of simulation setups is chosen and systematically carried out, often by different commanders and at a variation of environmental conditions like wind force and direction, tidal currents or water depths.

4 CASE STUDY: CANAL GHENT-TERNEUZEN

Different types of simulation will be explained and applied to a bulk carrier sailing southbound on the Canal Ghent-Terneuzen (CGT). This canal was originally dug in 1823 to connect the city of Ghent (Belgium) via the river Scheldt with the North Sea. In Terneuzen (The Netherlands), where the canal connects with the Western Scheldt, different locks in varying sizes were built. Nowadays, three locks are available. The West Lock is the largest with a length of 290 m and a width of 40 m, allowing a maximum fresh water draft of 12.5 m. In 2012 it was decided to build a new and larger lock in Terneuzen with a length of 427 m and width of 55 m. The lock is expected to be operational in 2022 (Sassevaart and Vlaams-Nederlandse Scheldecommissie, 2018).

The distance between the Port of Ghent (since 2017 *North Sea Port,* together with Flushing and Terneuzen in the Netherlands) and the locks in Terneuzen is about 10 nautical miles (18 km) and the narrowest (theoretical) section on the canal is a trapezoid which is 62 m wide at the full canal depth of 13.5 m and 155 m wide at the free surface (Figure 7).

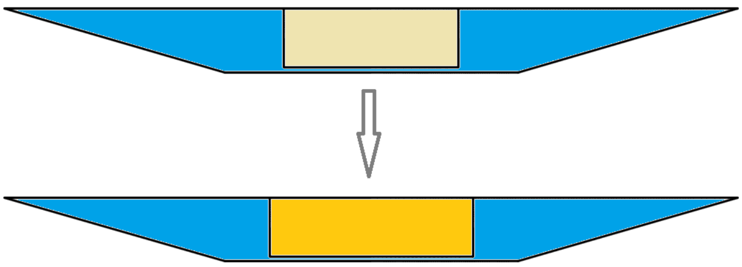


Figure 7 Smallest theoretic cross section of the Canal Ghent Terneuzen with midship sections of a ship BxT 37x12.5m² and 43x12.5m²

Nowadays, the draft of the vessels on the Canal is restricted to 12.50 m, which leaves a gross under keel clearance of 1 m or 8%. The largest vessels are bulk carriers, which are either of Panamax type (breadth 32.2 m, length over all up to 265 m) or Kamsarmax type (length over all 230 m, breadth 37 m). The maximum allowed speed for vessels with a draft of more than 10 m is 9 km/h, 12 km/h for vessels with a draft in between 4 and 10 m and 16 km/h for vessels with a draft of less than 4 m. The bottom section of the Canal is too narrow to allow meetings between large ships. The main challenges for captains and pilots on the canal are: the narrow cross-section (with a blockage of 32 % for the ships with BxT 37x12.5 m²), the bends, the passage of bridges which restrict the available width, and the bank effects. With respect to the latter, it can be stated that the effects of the port and starboard side banks more or less compensate each other in case of a centric course, but on different locations the symmetry is disturbed due to the presence of side docks. This will lead to transient bank phenomena which are much more difficult to handle than steady effects.

4.1 Example 1: FT Track Captive at CGT

On March 14th 2017 a full-scale measurement campaign was carried out on a bulk carrier (LxBxT 229.5x36.9x12.5 m³) sailing southbound on the Canal Ghent-Terneuzen. The results of this accurate position measurement was then used for the input of *FT Track Captive* simulations. Based upon the positions first all accelerations (in the horizontal plane) are defined. Then these accelerations are listed to be used as input for the simulation.

Figure 8 Trajectory from the full-scale measurements and FT Track Captive simulations on the CGT

In Figure 8 the position of the bulk carrier from the full-scale measurement is plotted together with the positions in the *FT Track Captive* simulation. Special attention should be drawn to the accuracy and definition of the inputted accelerations. Small deviations in the accelerations may result in too large drifting of the absolute positions.

Having a simulation of a full-scale measurement gives the opportunity to investigate the forces and moments the ship undergoes into more detail. The squat of the ship at full-scale can be compared with the squat of the same ship, but also forces like bank effects which cannot be measured at full-scale can be investigated in more detail.

4.2 Example 2: FT Track Predefined Controls at CGT

If the trajectory of the full-scale measurement would be plotted together with the trajectory from the *FTT Predefined Controls* based upon the rudder and propeller settings of the full-scale measurements. The deviations between both increase the longer the simulation takes because there is no feedback in the control system between the desired position (from the full-scale measurement) and the position in the simulation. The settings of propeller rate and rudder angle are set before the start of the simulation and the simulation simply picks the predefined propeller rate and rudder angle for each time step. Because of the force equilibrium another position in the small Canal will result in (very) different bank effects which results in a different position which results in different bank effects and so on and so forth.

4.3 Example 3: FT Track Controller at CGT

Figure 9 FT Track Controller trajectory of a 43m wide bulk carrier leaving the lock at Terneuzen sailing southbound on the Canal Gent-Terneuzen

When the new lock in Terneuzen is finished, larger ships are expected on the CGT. To investigate the nautical impact and to find the bottlenecks on the Canal for such a new type of vessel, *FT Track Controller* simulations can systematically investigate and point out the expected issues on the canal. Figure 9 shows the trajectory of a 43 m wide bulk carrier (which does not fit at present into the existing lock of Terneuzen) sailing on the Canal Gent Terneuzen. One of the findings of the simulation was that the longitudinal resistance force on the ship increased significantly compared to sailing in open water. This increase of resistance is related to the increased blockage (ratio between midship area and canal cross section area), as can be seen in Figure 7 as well as the small under keel clearance (water depth,13.5 m to draft 12.5 m ratio). This under keel clearance will even decrease more because of the squat of the ship when sailing at a forward speed through the canal.

4.4 Example 4: Real-time simulation at CGT

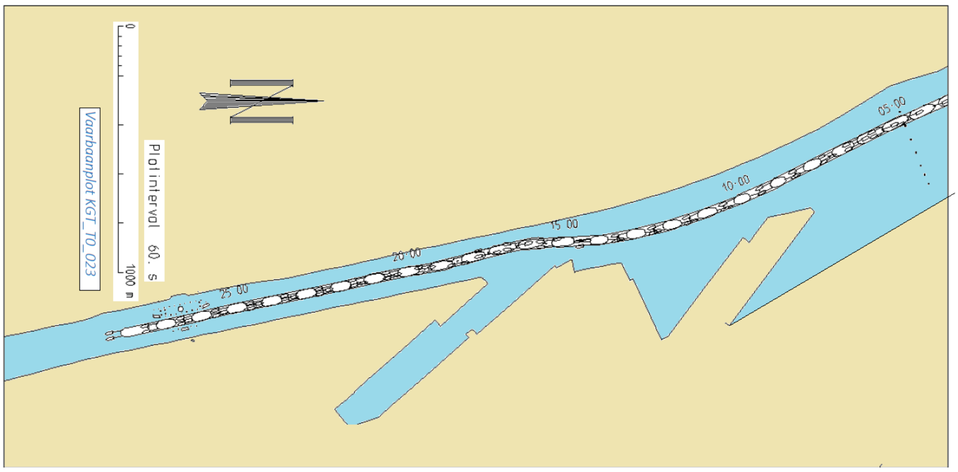


Figure 10 Trajectory of a Real-time simulation with a bulk carrier sailing from the lock at Terneuzen up to the crossing of the bridge at Sluiskil

In Figure 10, the last section of a 27 minute long trajectory is plotted of a real-time simulation with a bulk carrier sailing southbound on the Canal Gent Terneuzen from close to the locks in Terneuzen until the crossing of the bridge at Sluiskil. A distance of about 3000 m is sailed in this simulation. In the research for investigating the impact of wider vessels on the Canal some parts on the Canal are selected for real-time simulations while the entire Canal was taken into account for the fast-time simulations. The combination of both (real-time and fast-time simulations) is a typical technique to have a wide systematic series of results for the entire scope of the research without spending too much time and resources during the (relatively) expensive real-time simulations.

5 CONCLUSIONS

The calculation core of a simulation is the so called mathematical model. In a real-time simulation a human controls the ship similar as in real life (tiller, telegraph, tug commands etc.), this control is the input of the mathematical model which updates at a high frequency to be able to generate a smooth projected image. When the same mathematical model is no longer fed with human commands then the simulations is a fast-time simulation. Four different types of fast-time simulations can be carried out and each has its own advantages and disadvantages. These four type of fast-time simulations together with the real-time simulations can provide a profound indication of the feasibility of the manoeuvrability a specific ship in a, for example, confined fairway.

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Simulation type	**Fast-time Position Captive**	**Fast-time Track Captive**	**Fast-time Track Predefined Controls**	**Fast-time Track Controller**	**Real-time human controlled simulation**
Human interaction	no				yes
captive/free running	captive		free running		
time step t(n-1) influences t(n)	no		yes		
accelerations	no	yes			
Force equilibrium	no, net forces present		yes		
time calc = time sim	no				yes
exact path is known before calculation	yes		no		
track	predefined (theory or derived from full-scale),	depends on accelerations	depends on mathematical model	depends on Track Controller	depends of human
controls	no, predefined	predefined accelerations	no, predefined rudder and propeller rate	through Track Controller and desired track	human (pilot, captain, skipper)
simulations/24h	+100	+100	<100	<50	10 to 20
advantages	fast, relatively low computing power	fast	fast	more realistic path than other fast-times	completeness
disadvantages	sensitive to realism of input track no force equilibrium	no forces equilibrium	sensitive to rudder and propeller rate settings	sensitive to Track Controller settings time-consuming	time consuming exact repeat not possible low number of tests/day rather expensive

Table 1 Overview of five types of simulations used at FHR