Simulation and navigation

Technical aspects – how accurate can simulators be?

François Hissel
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Développement durable
Infrastructures, transports et mer
Ressources, territoires et habitats
Énergie et climat
Prévention des risques

Présent pour l'avenir

Outline

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1. Context
   - The simulator and its possible uses
   - Benefits of the simulator
   - Drawbacks of the simulators
2. Technical aspects
   - General overview
   - Physics of inland navigation
   - Immersion into the virtual universe
   - The rules of the game
3. Synthesis

What is a simulator?

Definition

A simulator is a device able to approximate one or several physical dynamical phenomenons by means of numerical modelling or analogy with a reduced model, and present the results to its user in an understandable way in order to make him learn the behaviour of the corresponding real system he would not be able to experience otherwise.

A nuclear power plant simulator

A plane simulator

A simulator for firemen operations

A flood simulator


Video generated with Hochwasser3D (IBDS & IWK, Uni KA)

A car simulator

Main benefits of the simulator

- Simulators are cheap
  - Not as expensive as a real ship for training
  - Not required to reserve a channel or a quay for manoeuvring operations
  - Common course for several students at the same time
  - Safe training experience
- Simulators allow to do "what-if,, experiments
  - Possibility to add difficult situations in an exercise: engine breakdown, lock, high traffic, another ship not deflecting from its normal trajectory
  - Possibility to play with time, to focus on different aspects of navigation or retry a failed attempt
  - Modeling of rare situations in terms of discharge, wind, waves, weather
  - Possibility to study the impacts of specific parameters by changing them one after the other

Cost-effectiveness and diversity of exercises

The use of a simulator decreases the costs of training or exams and allows to test the behavior of the pilot in rare and extreme conditions.

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- Simulators can represent different kinds of ships
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    - Several students can interact with ships (merchant boat and tug boat)
- Simulators can include additional tips
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  - Recording of the exercise to replay it with the student and evaluate its piloting choices
  - Possibility to automate the teacher's task, so that the whole knowledge can be saved and transmitted
- Simulators may exist at different scales
  - Students can have their own version of the software to exercise at home

Freedom of use and wealthness of training

The use of a simulator in inland navigation courses improves the relationship between the student and his trainer and allows a personal work.

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Other possible uses of a simulator

- Simulators can help design new structures and channels
  - When designing a channel, it is important to test its sizing against the needs for a safe manoeuvring of ships. This is only possible with the simulator since the channel does not exist yet.
- Simulators facilitate communication to the general public
  - A simulator is a support to show the effects of a new planning policy
  - A simulator can be used for touristic purposes, to help the general public discover a city or the countryside

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- A simulator is based on a numerical model
    - Never as rich as the real world: some phenomenons can not be represented due to strong constraints in calculation time. The whole model is as weak as the weakest component.
    - Always a slight chance that the computation yields false results. It is needed to double-check the behaviour of the ship in the simulation in all the conditions it will be used.
- A simulator uses a virtual environment
    - Bad feeling of danger because of the virtual world to which the student does not belong. This may impact future behaviour in real life.
    - Usually no physical representation of the movement of the ship.

Simulation is not reality

A training on a simulator will never replace a training on a real ship. Simulators may become part of the curriculum of the new pilots but driving lessons on a real boat will still be mandatory.

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- Simulators may be expensive
    - A good knowledge of involved phenomenons is necessary, which always goes through measures on real ships or scale-down models
    - The computation requires high-performance computers. For a realistic cabin, one needs screens and instruments.
    - The more realistic the virtual environment is, the more photographic campaigns are needed to make it look like the real world
- Simulators need maintenance and adapted training
    - Maintenance is an issue of computer engineering which is not the specialty of training institutions
    - Materials must be replaced when they fail
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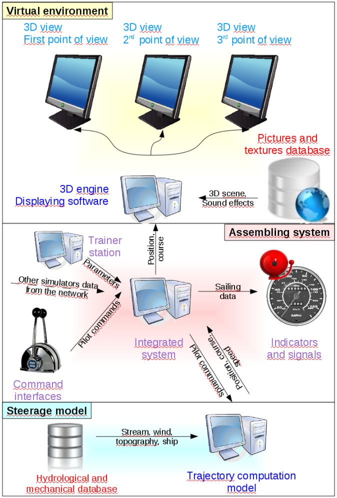
Overview of the components of a simulator



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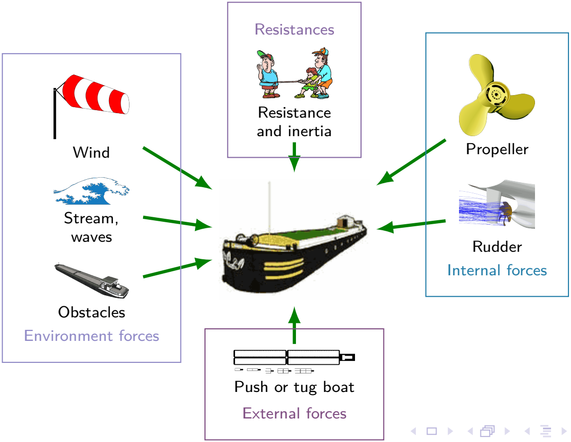
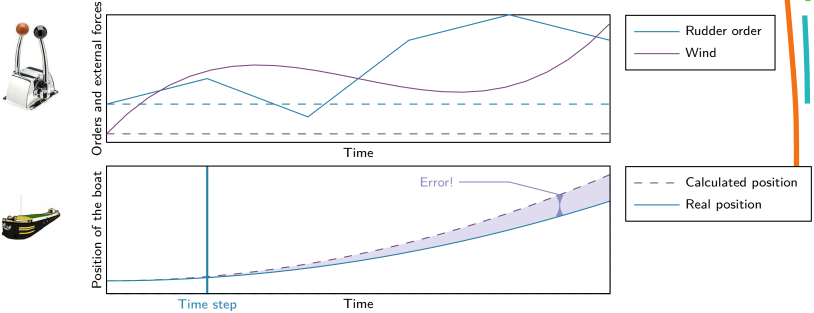


Why is simulation difficult?

All the forces may change over time, therefore the equations must be solved for many successive time steps.



The challenge of simulation

An accurate simulation needs a small time step but a lower bound is the time required by the calculation.

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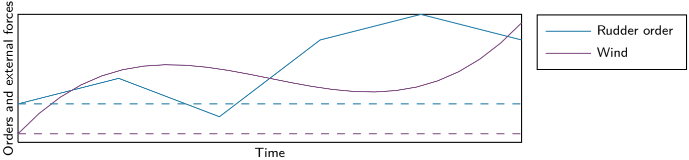

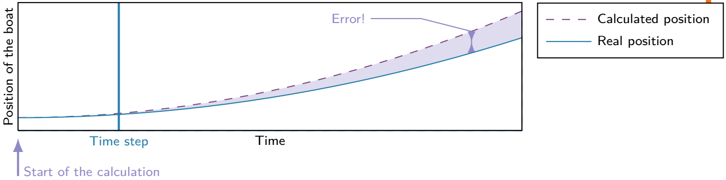

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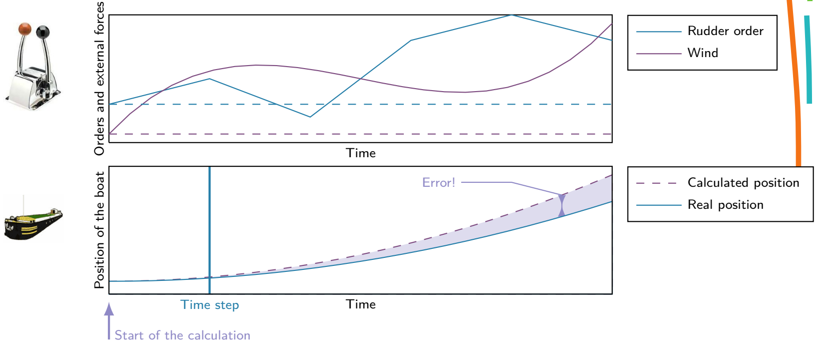

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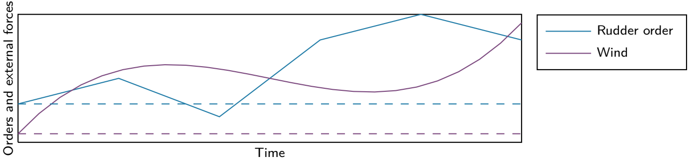
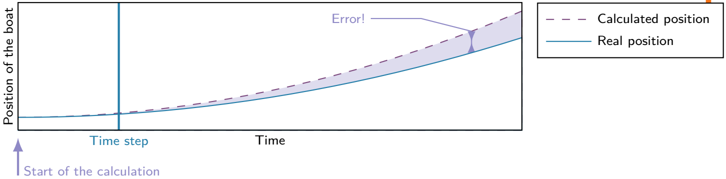
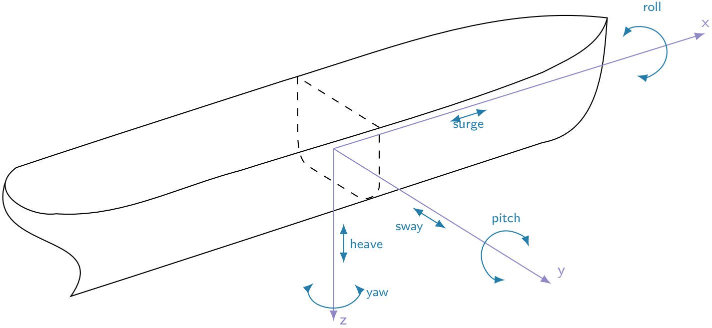




The challenge of simulation

An accurate simulation needs a small time step but a lower bound is the time required by the calculation.

An important parameter: the degrees of freedom



When are the degrees of freedom needed?

Degree of freedom	Use
Surge	Always
Sway	Always
Heave	Grounding, fuel consumption, shallow water
Yaw	Always
Roll	Waves, high loading or liquid cargo
Pitch	Long waves (not in rivers)

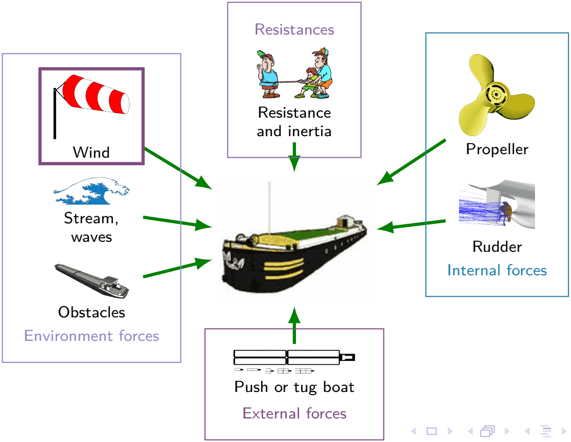
Degrees of freedom

More degrees of freedom make the simulation more realistic and allow to represent more phenomenons, but affects the speed and complexity of the model.

Physics of the model

The simulator calculates the movement given external and internal forces.

$$M(1+k)\frac{d\underline{V}}{dt} = \underline{F_{\text{wind}}} + \underline{F_{\text{water}}} + \underline{F_{\text{propulsion}}} + \underline{F_{\text{rudder}}}$$



Resistances

Resistance and inertia

Wind

Stream, waves

Obstacles

Environment forces

Propeller

Rudder

Internal forces

Push or tug boat

External forces

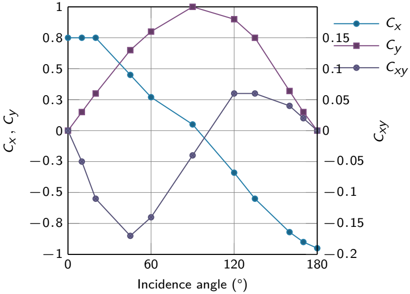
Wind forces

Wind forces depend on:

- the actual wind (with screen effects),
- the orientation of the apparent wind compared to the ship,
- the geometry of the boat,
- the ship's loading.

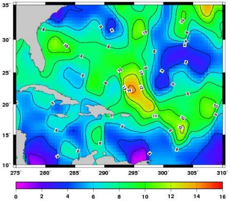
Wind forces on the ship:

$$\begin{cases} F_x = \frac{1}{2}\rho_a C_x A_t V^2 \\ F_y = \frac{1}{2}\rho_a C_y A_l V^2 \\ M = \frac{1}{2}\rho_a C_{xy} L A_t V^2 \end{cases}$$



How is wind taken into account?

Wind has a strong influence on trajectory. Therefore all simulators must take it into account.



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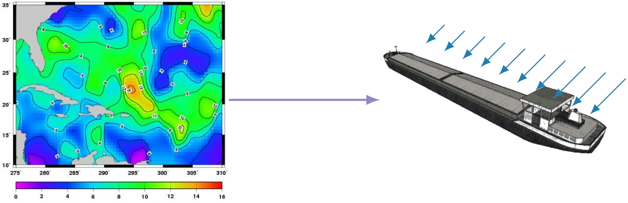

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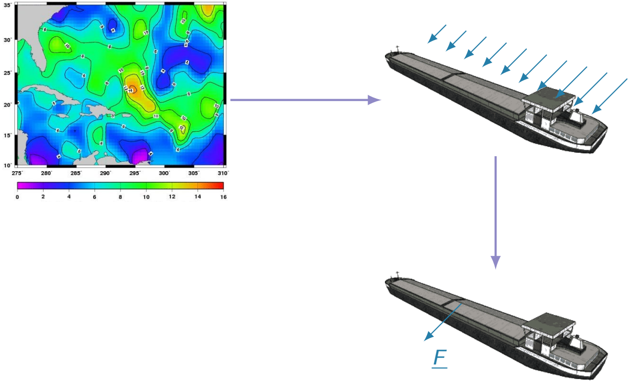

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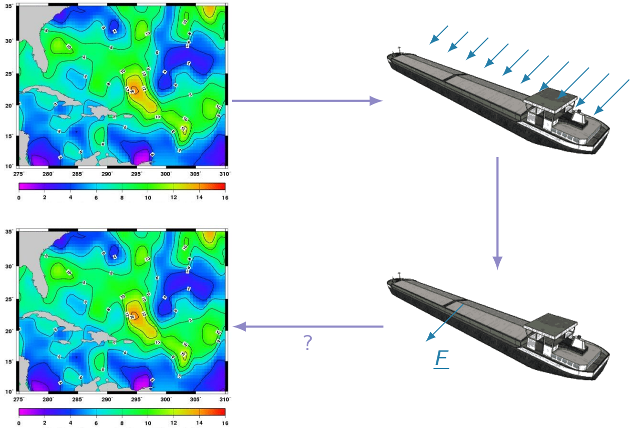

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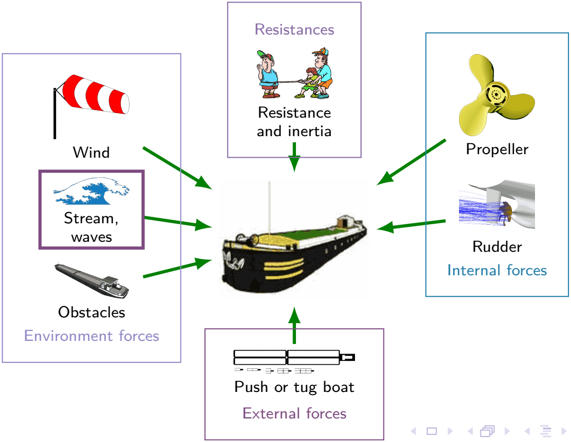

Resistances

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Rudder

Internal forces

Push or tug boat

External forces

Hydrodynamic forces

Different effects:

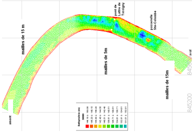
- Resistance to the movement
- Additional force due to the stream
- Squat
- Pressure effects when close to another object (bank, boat, bridge)

Stream effects

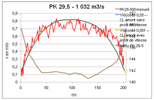
Stream effects are calculated through a numerical resolution of shallow-water equations for given boundary conditions (discharges, water levels, tide):

$$\begin{cases} \dfrac{\partial h}{\partial t} + U\dfrac{\partial h}{\partial x} + h\dfrac{\partial U}{\partial x} = 0 \\ \dfrac{\partial U}{\partial t} + U\dfrac{\partial U}{\partial x} + g\cos\alpha\dfrac{\partial h}{\partial x} = g\sin\alpha - \dfrac{C_f}{2}\dfrac{U|U|}{h} \end{cases}$$

A 2D-model is usually enough for the calculation of forces. Multilayer 2D models or 3D models provide additional insight in the velocities of water across the depth.

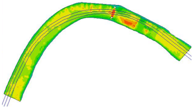


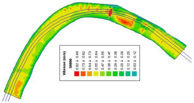
Bathymetry



Calibration on measures

Water velocities for low discharge

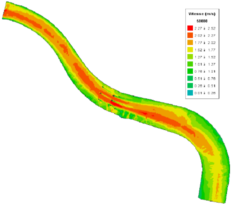




Water velocities for high discharge

How are hydrodynamic forces taken into account?

Hydrodynamics effects are a crucial part of the mathematical model and all simulators must take them into account.



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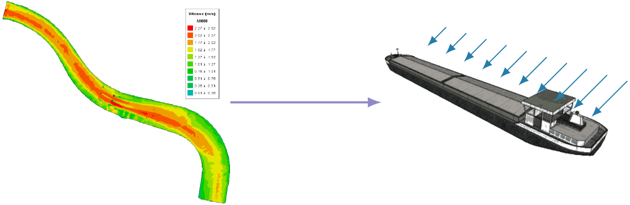

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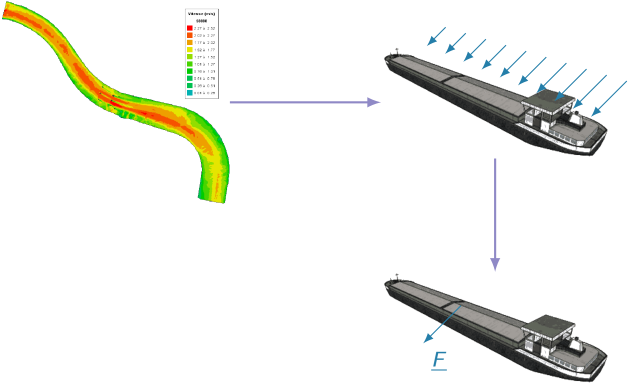

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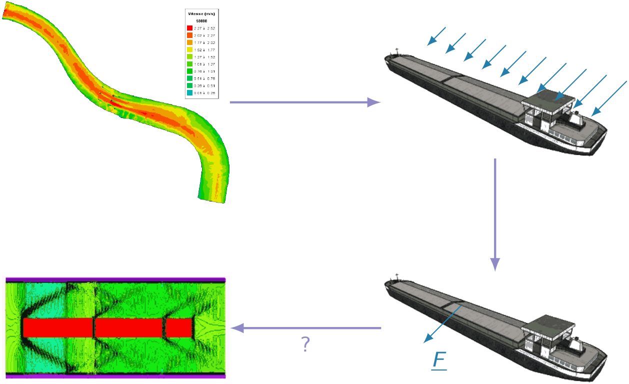

Advantages of models

	2D model	**3D model**
Executed once	Stream Resistance to propulsion Waves	Deep streams (temperature gradient)
Real-time		Squat Boat waves

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	2D model	**3D model**
Executed once	Stream Resistance to propulsion Waves	Deep streams (temperature gradient)
Real-time		Squat Boat waves

Increasing complexity

Physics of the model

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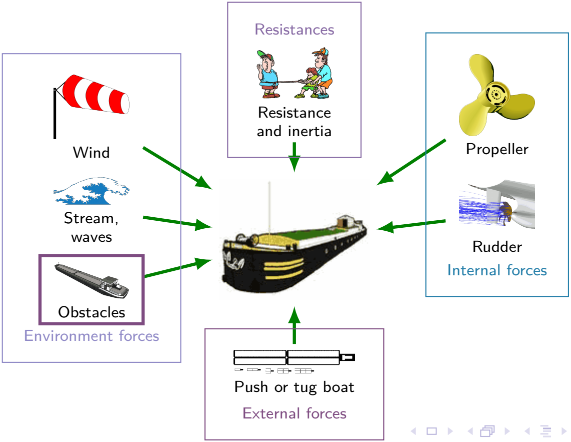

Resistances

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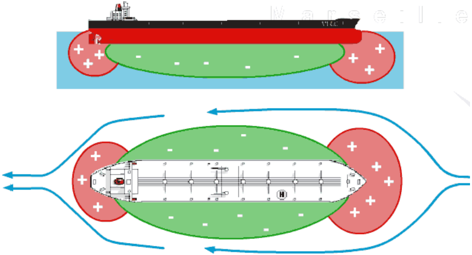
Pressure effects

A boat sailing with a given velocity creates two areas of high pressures at his stern and his bow and an area of low pressure all under its hull.

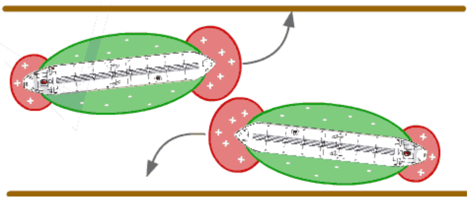


Credits: H. Boudu

The first effect of this pressure is squat that may cause grounding.

Venturi's effect

When the boat is nearing an obstacle (another boat, a bridge or the bank), pressure effects tend to change its trajectory.



Credits: H. Boudu

Effects of pressure

Pressure is a dynamic effect that influences maneuvering in confined channels or near obstacles. An accurate calculation requires a real-time fluid model and high computation power, but empirical models provide good approximations of the effects.

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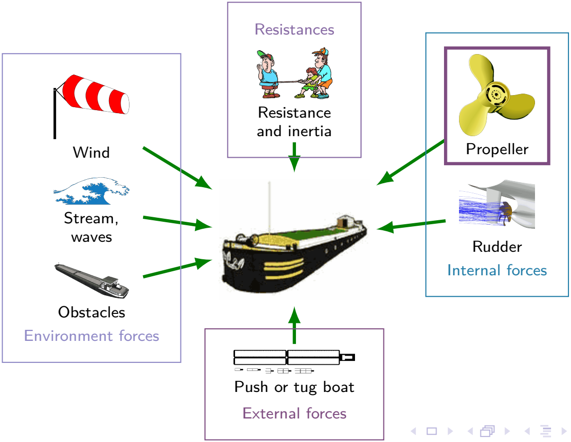

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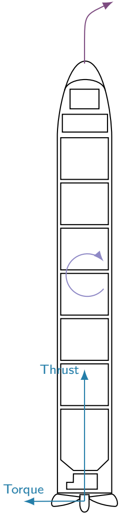
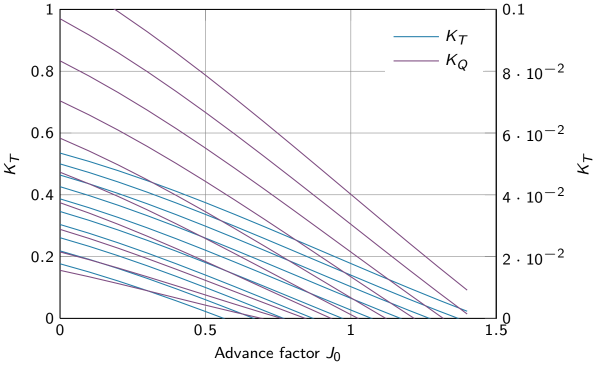
For each propeller, we calculate a thrust and a torque moment.

$$\begin{cases} J_0 = \dfrac{V_0}{nD} \\ T = K_T \rho n^2 D^4 \\ Q = K_Q \rho n^2 D^5 \end{cases}$$





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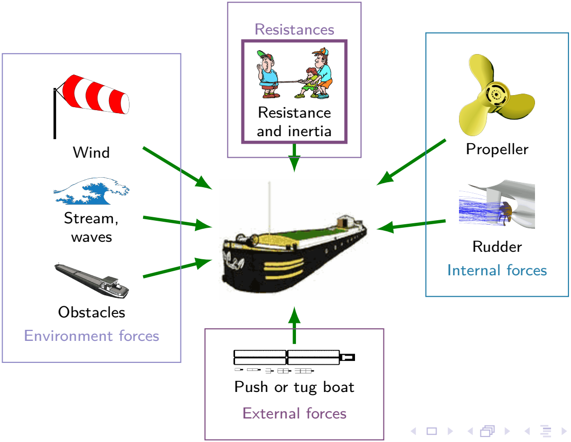
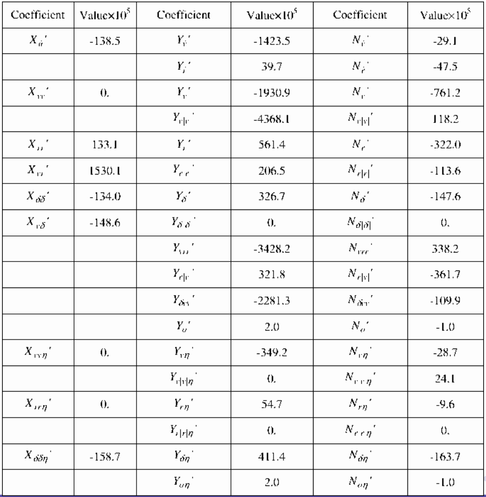


Hydrodynamic coefficients

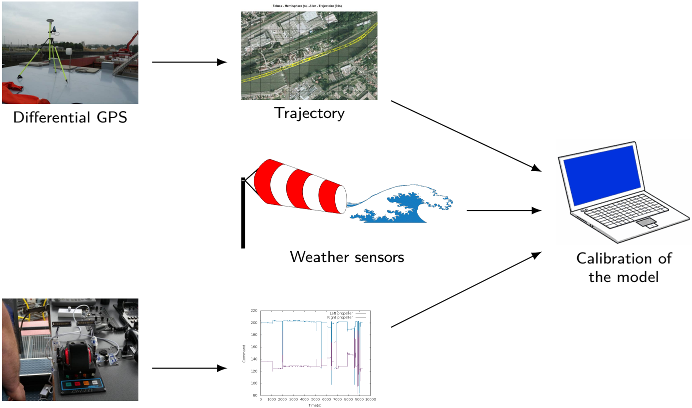
Since hydrodynamic effects are too complex, they are summarized by several dozens of coefficients which are calibrated on in-situ or reduced models.



Coefficient	Value×10^5	Coefficient	Value×10^5	Coefficient	Value×10^5
$X_{\dot u}'$	-138.5	$Y_{\dot v}'$	-1423.5	$N_{\dot v}'$	-29.1
		$Y_{\dot r}'$	39.7	$N_{\dot r}'$	-47.5
X_{vv}'	0.	Y_v'	-1930.9	N_v'	-761.2
		$Y_{v\|v\|}'$	-4368.1	$N_{v\|v\|}'$	118.2
X_{rr}'	133.1	Y_r'	561.4	N_r'	-322.0
X_{vr}'	1530.1	$Y_{r\,r}'$	206.5	$N_{r\|r\|}'$	-113.6
$X_{\delta\delta}'$	-134.0	Y_δ'	326.7	N_δ'	-147.6
$X_{v\delta}'$	-148.6	$Y_{\delta\,\delta}'$	0.	$N_{\delta\|\delta\|}'$	0.
		Y_{vrr}'	-3428.2	N_{vrr}'	338.2
		$Y_{r\|v\|}'$	321.8	$N_{r\|v\|}'$	-361.7
		$Y_{\delta v}'$	-2281.3	$N_{\delta v}'$	-109.9
		Y_o'	2.0	N_o'	-1.0
$X_{vv\eta}'$	0.	$Y_{v\eta}'$	-349.2	$N_{v\eta}'$	-28.7
		$Y_{v\|v\|\eta}'$	0.	$N_{vv\eta}'$	24.1
$X_{rr\eta}'$	0.	$Y_{r\eta}'$	54.7	$N_{r\eta}'$	-9.6
		$Y_{r\|r\|\eta}'$	0.	$N_{rr\eta}'$	0.
$X_{\delta\delta\eta}'$	-158.7	$Y_{\delta\eta}'$	411.4	$N_{\delta\eta}'$	-163.7
		$Y_{o\eta}'$	2.0	$N_{o\eta}'$	-1.0

In-situ calibration of hydrodynamic coefficients

In-situ calibration requires a full set of measures of trajectory and orders of the pilots.



Differential GPS

Trajectory

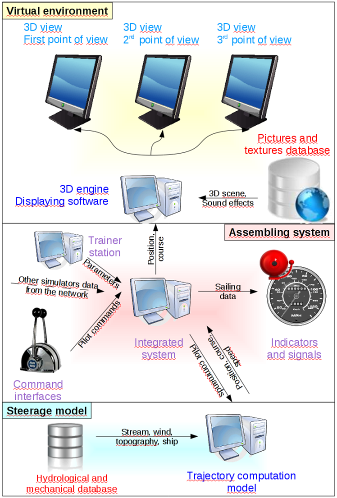
Weather sensors

Calibration of the model

On-board sensors for thrust and rudder

Time graph of orders

Overview of the components of a simulator



Overview of the components

DST simulator in Duisburg (photo F. Hissel)

Overview of the components

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☐ Physical controllers

Overview of the components

DST simulator in Duisburg (photo F. Hissel)

☐ Physical controllers ☐ Visual display

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DST simulator in Duisburg (photo F. Hissel)

☐ Physical controllers ☐ Visual display
☐ Aural display

Overview of the components

DST simulator in Duisburg (photo F. Hissel)

☐ Physical controllers ☐ Visual display
☐ Aural display ☐ Control devices

Physical controllers

Physical controllers provide the input to the simulator. They translate the orders of the pilot in values understandable by the software.
Minimum requirements:

- Propellers and rudder commands, bow thruster
- Placement like in a real ship
- Adapted to the equipment of the boat (type of propeller)
- Customizable to represent different kinds of boats including future ones

Physical controllers

Physical controllers are the heart of the interaction between the student and the simulator. They are easy and cheap to design.

Control devices

The following control devices are required:

- Indicators of shaft revolution and pitch of propellers
- Indicators of rudder angles and rate of turn
- Relative wind direction and force
- Compass (optional)

Control devices

Control devices are easy to set up and do not contribute much to the cost of the simulator.

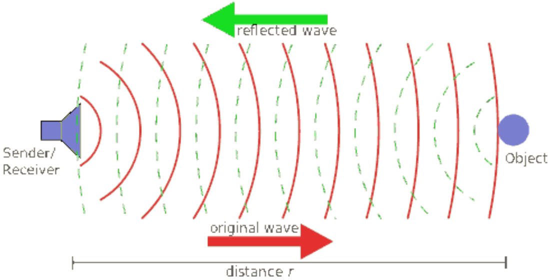
Other devices

Other devices that have to be added to the cabin are:

- ECDIS maps
- Inland AIS
- GPS
- Echo-sounder
- Communication equipments (VHF)

Radar

A full simulation of radar needs heavy calculation.



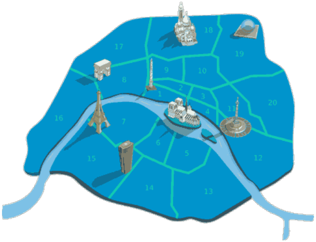
Radar

Radar is a necessary device but requires an accurate knowledge of the close environment, including materials, and a processor dedicated to the calculation of the wave propagation.

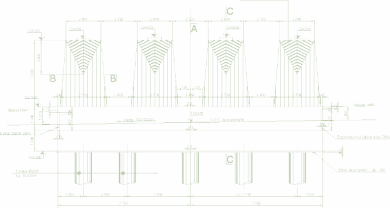
3D model of the surroundings

Construction of a 3D model

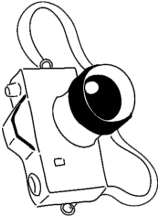
The first step to build a new 3D model is to get geometrical data about the scene.



Topographic and buildings maps

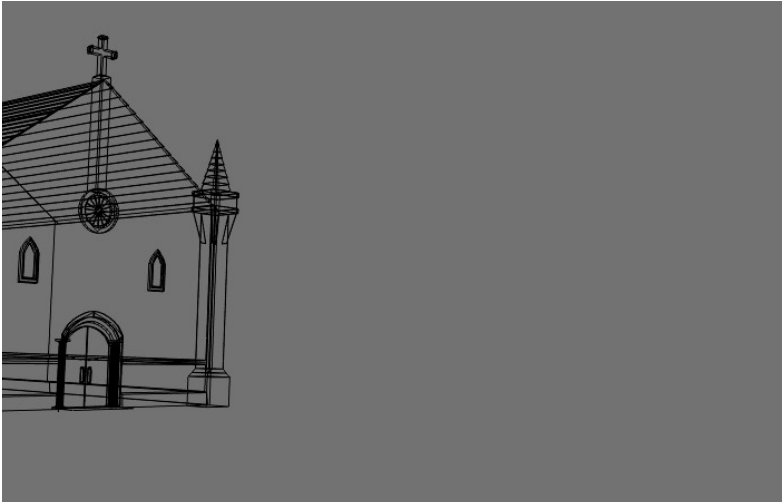


Blueprints of structures

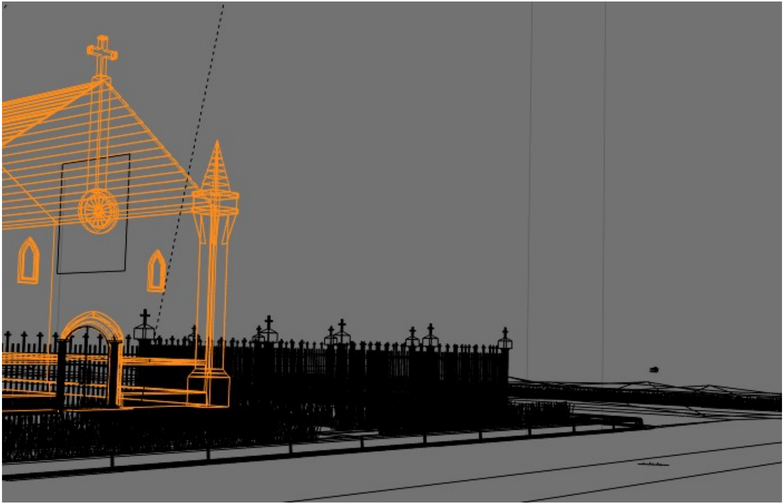


On-site visits

Construction of a 3D model



Addition of details



Materials

Textures

Background

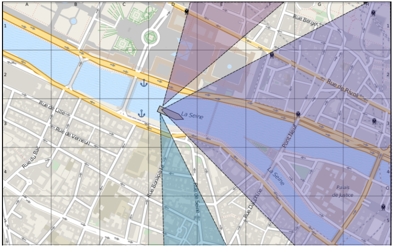
Rendering

Weather

Day and night

Calculating points of view

For each point of view, an image has to be rendered at least 20 times per second.



Points of view

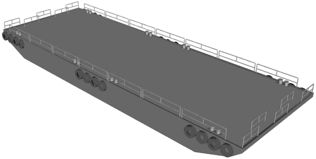
When the 3D model is ready, it is easy to add a point of view, but you need a dedicated graphic processor.

Virtual environment in a simulator

In a simulator, some elements are required because they are used as landmarks by the students:

- Meteorological effects (fog, rain)
- Day and night alternance
- Height of water
- Navigational marks

Boats modeling



For an inland simulator, the following boats are advised:

- Small vessel (or tug)
- Medium (86m)
- Large (110 to 135m)
- Formation
- 4-barges push array

Virtual reality

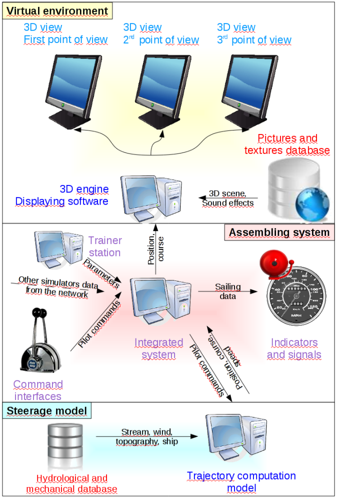
Other details may be added for a more realistic experience:

- Movement of water
- Light reflection and refraction on the surface of the water
- Dynamic objects (air socks, locks, terrestrial vehicles. . .)

Virtual reality

The process of building 3D models for sites or boats is long and expensive, but only has to be done once. The number of details represented is only limited by the computation power.

Overview of the components of a simulator



The conductor's job

The teacher has a global view of the position of all student ships and can provoke changes in the environment:

- Change of weather or wind
- Change of discharge or water depth
- Equipment breakdown
- Simulation of other target boats
- Move the boat and change its speed to test the student

Features of the teacher's station

To improve the quality of exercises, the teacher's station must have additional features:

- Record the exercise and all relevant data to be able to display it later
- Restart an exercise at some point in the past
- Freeze a running exercise to discuss difficulties
- Communicate with the student through VHF stations

Outline

What is required for any simulator?

Core models
- 🟩 3D engine
- 🟩 Mathematical model
- 🟩 Radar model

Boat models
- 🟩 3D-model
- 🟧 Calibrated hydrodynamic model

Site models
- 🟥 3D-model
- 🟧 Calibrated hydraulic model

Material
- 🟥 Cabin(s)
- 🟩 Control devices
- 🟩 Physical controllers
- 🟥 Screens
- 🟧 Teacher's station

🟩 Cheap 🟧 Average 🟥 Expensive

From curriculum to features – General operation

What must the pilot know?	Consequences for the simulator
Radar	Suited 3D model of sites Radar simulation, radar screen
Electronic chart	Screen with ECDIS display
VHF radio equipment	Equipment
Anchor controls	Anchor commands Mathematical model with forces on boat
Navigation lights controls	Lights commands Dynamic lighting in 3D model
Engine controls and alarms	Engine commands and screens for display
Internal communication equipment	Equipment in cabin
Inland AIS	Equipment AIS simulation

From curriculum to features – Navigation conditions

What must the pilot know?	Consequences for the simulator
Clear weather, day, dawn, night, rain, snow	Basic raytracing in 3D model
Different types of waterways (canal, river)	Variety of modeled sites
Waters with and without current, different water levels	Hydraulics model with different boundary conditions
Estuaries and downstream rivers	Tide model Dynamic setting of water level in 3D model
Strong wind	Mathematical model for wind and wind force

From curriculum to features – Special maneuvers

What must the pilot know?	Consequences for the simulator
Lock	Lock operation Hydrodynamics model for lock entrance Collision model
Bridge	Bridge in 3D model and in hydraulics model
Crossing a river with current, entering port from river	Hydraulic model
Passing through narrowed stretch or near moored ships Overtaking ships	Hydrodynamic model with confinement effects
Mooring and unmooring	Moor model

From curriculum to features – Impacts on maneuvers

What must the pilot know?	**Consequences for the simulator**
Effects of available water depth	Hydrodynamic model with confinement effects One more degree of freedom
Ship's speed	Calibrated mathematic model
Loading condition	Different calibrations for different loading situation
Proximity of walls, banks, other vessels	Hydrodynamic model with confinement effects One more degree of freedom

From curriculum to features – Other

What must the pilot know?	**Consequences for the simulator**
Calculate a safe passing height under a bridge	Movable wheelhouse in 3D model 3D collision model
Safe navigation according to police regulations	Signals in 3D model

What makes a good training simulator?

- The purposes of the training are clearly defined
- It feels like the real world
- It focuses on the key aspects of training at the expense of details
- The exercises and their outcomes are believable
- It includes tracking of the choices of the student

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Thank you for your attention!