NTNU


MARITIME ROBOTICS

**IFAC World Congress 2008 Pre-Conference Workshop 5**
**Cooperative Control of Multiple Autonomous Vehicles**
**Sunday July 6, 2008**

# Formation Control for Unmanned Surface Vehicles:

# Theory and Practice

**Morten Breivik**
{Centre for Ships and Ocean Structures,
Department of Engineering Cybernetics};
Norwegian University of Science and Technology;
Trondheim, Norway

**Vegard Evjen Hovstein**
CEO, Maritime Robotics AS
Trondheim, Norway

CESOS

# Outline

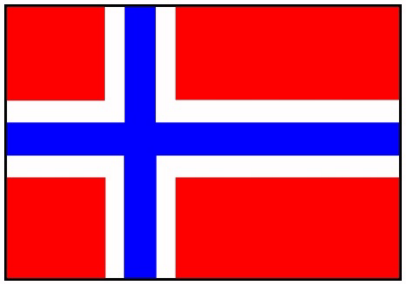


- Norway and Norwegian Actors
- USV Motivation
- Past and Present USVs
- Legal and Commercial Issues
- USV Motion Control
- USV Formation Control
- Future Challenges
- Conclusions

# Norway



- Population: 4.65 million (2008).
- The size of California.
- Biggest industries:
  - Oil and Gas
  - Shipping and Aquaculture
  - Wood
- Web site: norway.com



# NTNU



- The Norwegian University of Science and Technology (NTNU):
  - Located in Trondheim (in the middle of Norway)
  - Has approximately 20 000 students (half of them in science and technology) and 3500 employees (faculty, staff)
  - Focus on:
    - Energy and Environment
    - Information and Communication
    - Medicine
    - Materials
    - Marine and Maritime
- Web site: ntnu.no

# CESOS



- The Centre for Ships and Ocean Structures (CESOS):
  - The goal is to "integrate theoretical and experimental research in marine hydrodynamics, structural mechanics, and automatic control"
  - 8 key researchers, 20 postdocs and 30 PhD students. Also have visiting professors and students
  - Financed by the Research Council of Norway as well as Norwegian industry (the Marine and Maritime Industry is a key focus area for Norway)

- Web site: cesos.ntnu.no

# Maritime Robotics



- Maritime Robotics develops and delivers Unmanned Surface Vehicle (USV) systems and services.
- The primary focus concerns applications for the oil and gas industry.
- Maritime Robotics takes leading Norwegian expertise in marine cybernetics, maritime sensors and maritime engineering into the unmanned future.

# USV R&D – MR/NTNU

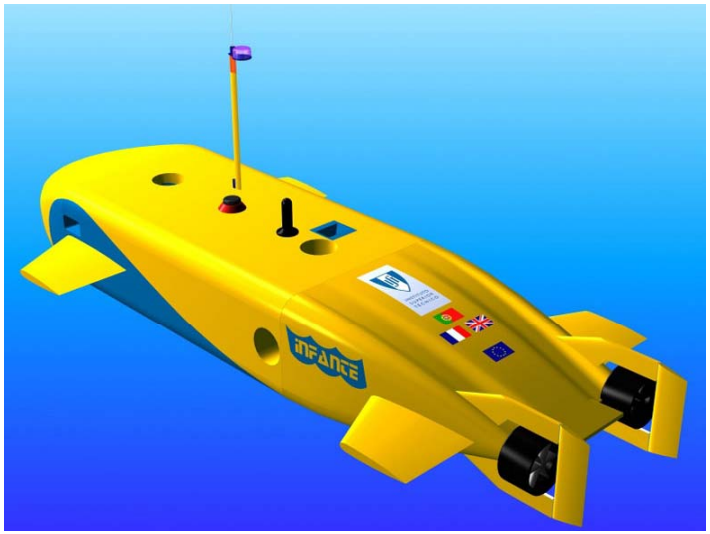


- Cooperation between NTNU and Maritime Robotics since 2006:
  - Involving project work and master theses
  - Funded by the Norwegian Research Council
- Collision avoidance:
  - Theoretical study
  - Simulation study
  - Initial full-scale testing (during the spring of 2008)
- Formation control:
  - Theoretical study
  - Simulation study
  - Initial full-scale testing (during the summer of 2008)

# USV Motivation



- When people hear about unmanned systems today, they mostly think about:
  - Unmanned Aerial Vehicles (UAVs)
  - Unmanned Underwater Vehicles (UUVs)
  - Unmanned Ground Vehicles (UGVs)
- Unmanned Surface Vehicles (USVs) have not been given as much attention as these three vehicle categories.
- In fact, only last year did the US Navy release its first USV Master Plan.




# USV Motivation



- Important definitions (taken from the USV Master Plan):
  - **Unmanned:** Capable of unmanned operation. Can be manned for dual use or test and evaluation. Has varying degrees of autonomy
  - **Surface Vehicle:** Displaces water at rest. Operates with near continuous contact with the surface of the water. Interface of the vehicle with the surface is a major design driver
  - **Manual:** Man in loop continuously or near-continuously
  - **Semi-autonomous:** Some vehicle behaviors are completely autonomous (e.g., transit to station, activate sensors). Vehicle refers to its operator when directed by the operator or by its own awareness of the situation (e.g., for permission to fire)
  - **Autonomous:** The vehicle governs its own decisions and makes its own decisions from launch point to recovery point

# USV Motivation



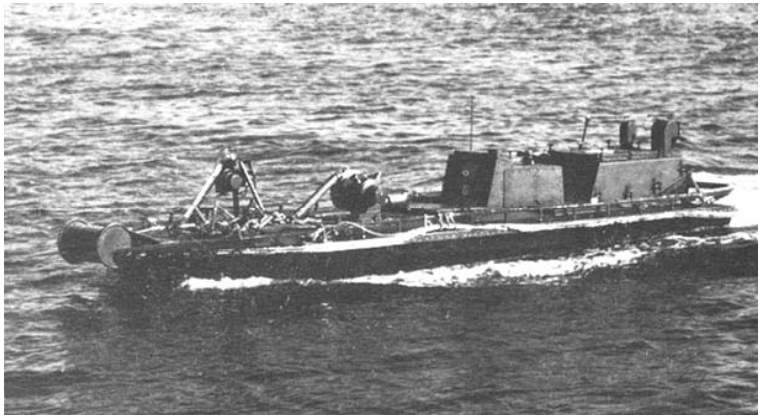
- USV technology harbors a great potential:
  - Reduced personnel cost
  - Less need for personnel in exposed areas
  - Reduced risk for and smaller consequences from operator errors
  - Increased operational precision
  - Flexible vehicles with reduced emission
  - Possibilities for new vehicle designs
  - New concepts of operation
- USVs can typically be used for so-called dirty, dull, and dangerous operations:
  - **Dirty:** Disaster monitoring, polluted or NBC-exploited areas
  - **Dull:** Maritime monitoring, communications relay for AUVs, geophysical survey
  - **Dangerous:** Military surveillance, extreme operations, and operations in remote areas (like, e.g., the Arctic)

# Past USVs



MARITIME ROBOTICS

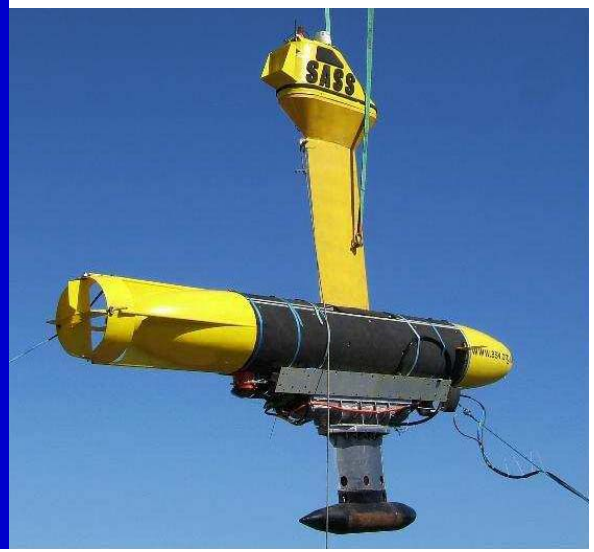
- USVs have been developed and operated since World War II, and a rough historical timeline encompass:
  - End of World War II:
    - Laying smoke for the Normandy invasion (COMOX)
    - Mine and obstacle clearance (Demolition Rocket Craft)
  - 1946:
    - Drone boats collecting radioactive water samples after atomic bomb blasts (on the Bikini Atoll)
  - 1954:
    - Remotely operated minesweeping boats (DRONE)
  - 1960s:
    - Target drone boats for missile firing practice and destroyer gunnery training
    - Munitions deployment (Drone Boat)
    - Minesweeping Drone (MSD) for use in Vietnam
  - 1990s:
    - Sophisticated minesweeping systems (R/C DYADS, MOSS, ALISS)
    - Autonomous features in the Remote Minehunting System (RMS)
    - Reconnaisance and surveillance missions (ASH, Roboski)



# Present USVs



- Current USVs include a spectrum of vehicle technologies, encompassing naval and scientific applications. No applications currently exist in the commercial market.
- A common trait for current USVs are their size. They are small, boat-like vehicles (up to around 11 meters in length).
- Most USVs of today have been adapted from manned surface vessel designs that must accommodate human occupants. However, this limitation need not apply to unmanned systems, which, e.g., can be designed as semi-submersibles for improved stealth and platform stability.




# Present USVs



- A majority of USVs under development are found in the US, and the technology is mainly developed for naval purposes.
- Most scientific USVs are just experimental platforms.
- Hull designs, communication and sensor systems, as well as control algorithms are tested.
- Current USVs are mostly remotely operated (or semi-autonomous at best). No fully autonomous USVs exist today.
- The only industrial-level USVs today are found within the naval segment, mainly for intelligence, surveillance, and reconnassaince (ISR) applications.
- Compared to the current UAV market and technology, USV development is still in its infancy.

# Legal Issues



- Legal considerations for the use of unmanned vehicles in manned seaways are essential.

- SOLAS (an agreement between IMO members), Chapter 4, Regulation 14, poses the possibly strictest condition:
  - "From the point of view of safety of life at sea, all ships shall be sufficiently and efficiently manned."

- Also, the Norwegian Maritime Directorate demands that:
  - Every maritime operation must have a captain in charge. In case of a USV, the captain can be located on the bridge of the manned mother vessel, as long as he has sensor-based and/or visual view of the operational area

- A lot of regulatory work remains to be done, and fortunately inspiration can be sought from ongoing work that is performed in the US regarding UAVs (operating in the NAS).

§

# Commercial Issues



- Commercial applications depend on the development of a legal framework that provide guidelines and render possible unmanned operations in traditionally manned areas.

- USVs for civil applications are in the "technology push" phase.

- Hence, key industrial challenges today include:
  - International regulations
  - More focus on the USV as a payload carrier:
    - Better integration of sensor systems
    - Offer a sensor carrier to the customer
  - The market demands reliable systems:
    - Semi-autonomous systems
    - Master-slave behavior

# USV Motion Control



- Start by defining two main operating spaces:
  - Work space (operational space): The physical space in which a vehicle moves
  - Configuration space (joint space): The vehicle's degrees of freedom (DOFs)
- Then define actuation capabilities:
  - Full actuation: A vehicle that is able to simultaneously control all its DOFs independently
  - Underactuation: A vehicle that is unable to simultaneously control all its DOFs independently
- A vehicle that is underactuated in its configuration space can still achieve meaningful tasks in the work space (however, typically lacking the ability to achieve arbitrary attitude assignments).
- At high speeds, most vehicles are underactuated in their configuration space anyway (e.g., aircraft, missiles, ships, underwater vehicles, etc.), and are forced to maneuver in an energy-efficient manner.
- Ships are typically underactuated above 1.5 – 2 m/s.

# USV Motion Control

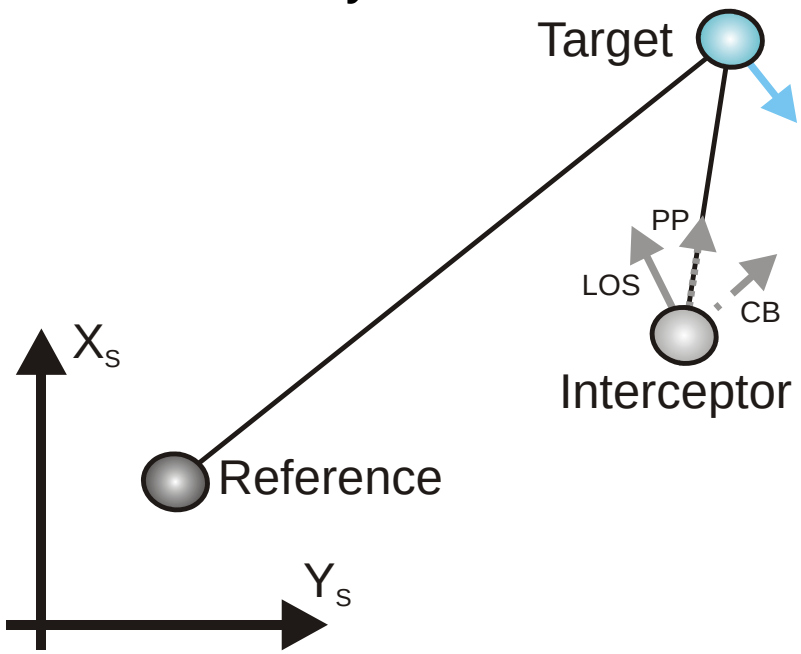


- Motion control scenario definitions (all motions and paths are considered in the work space):
  - **Target tracking:**
    - The control objective of a target-tracking scenario is to track the motion of a target that is either stationary or that moves such that only its instantaneous motion is known, i.e., such that no information about the future target motion is available
    - Thus, it is impossible to separate the related spatio-temporal constraint into two separate (spatial and temporal) constraints
  - **Path following:**
    - The control objective of a path-following scenario is to follow a predefined path, which only involves a spatial constraint
  - **Path tracking:**
    - The control objective of a path-tracking scenario is to track a target that moves along a predefined path, which means that it is possible to separate the spatio-temporal constraint into two separate constraints
  - **Path maneuvering:**
    - The control objective of a path-maneuvering scenario is to employ known maneuver capabilities to feasibly negotiate a predefined path
    - This approach might value spatial constraints over temporal constraints if the latter will lead to violation of the former

# USV Motion Control



- Hence, the motion control scenarios are defined based on what motion information is available apriori.
- In this aspect, the target tracking scenario constitutes the greatest challenge (without any apriori motion information).
- Guided missiles typically face target tracking scenarios, and guidance methods have already been developed to handle such encounters satisfactorily:



# USV Motion Control



- We choose to consider the target-tracking problem since it is the most challenging one.
- A motion control system that handles target-tracking scenarios will also be able to handle path-following and path-tracking scenarios (where apriori motion information can be used to optimize the performance).
- We suggest a concept that is illustrated by a case study of a 1-dimensional mass-damper (MD) system (analogous to the surge subsystem of a marine surface vessel):

$$\begin{aligned} \dot{x} &= v \\ m\dot{v} + d(v)v &= \tau(n) \end{aligned}$$

where $d(v) = (d_{\mathrm{l}} + d_{\mathrm{nl}}\,|v|)\,, \tau(n) = k\,|n|\,n$ , and $n \in [0, 5]$.

# USV Motion Control



- The dynamics of this system are unknown, and we are only able to apply the actuator control input while simultaneously recording corresponding position and speed outputs to find purposeful relationships that can be used for motion control design.

- Ultimately, we want to develop a simple, yet advanced motion control system that requires a minimum of system identification and tuning tests to be carried out in order for it to perform satisfactorily, and that inherently takes actuator constraints into account.

- Specifically, we apply so-called maneuverability and agility tests to find the relationships we need for design of a such a motion control system for the 1D MD system.

# USV Motion Control



- For a surface vessel, the relevant maneuver states include the surge speed u, the sway speed v, and the yaw rate r. These variables determine how fast the vessel can move on the sea surface (i.e., traverse the position and orientation - pose - space).
- The agility of a vessel describes how fast it can transition between its maneuver states.
- A lot of factors determine the maneuverability of a vessel, but the most important one for control purposes is the relationship between the actuator inputs and the maneuver states.
- All actuators are ultimately controlled by either a voltage or a current signal, such that their capacity can be conveniently represented in the range [-1,1] (abstracting away the actual signal range), where 1 represents maximum output.

# USV Motion Control



- For a vessel whose actuator setup corresponds to that of having a stern-mounted propeller and a rudder, tests can carried out in which the control signal for both actuators are applied in steps to cover their entire signal range while simultaneously recording the steady-state response of the relevant maneuver states.

- The test results will ultimately constitute a 5-dimensional surface - a maneuver map - in the combined input (propeller, rudder) and output (surge, sway, and yaw speeds) space, which is the input-output surface that the vessel nominally will be able to traverse.

- The tests should be carried out in ideal conditions, i.e., for minimal environmental disturbances and for nominal loading conditions.

# USV Motion Control



- Hence, the results can be used to design a feedforward controller that nominally will be able to achieve any allowable set of speeds by simply allocating the required control inputs derived from the maneuver map.

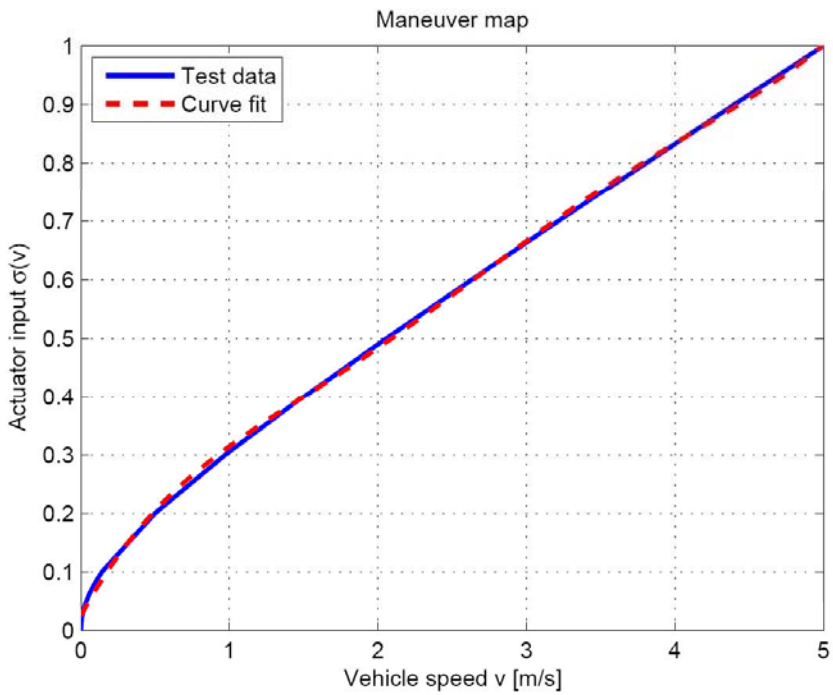
- Feedback terms must also be added to take care of any discrepancies between the nominal maneuver map and the actual situation, resulting, e.g., from changing environmental conditions and/or off-nominal loading conditions.

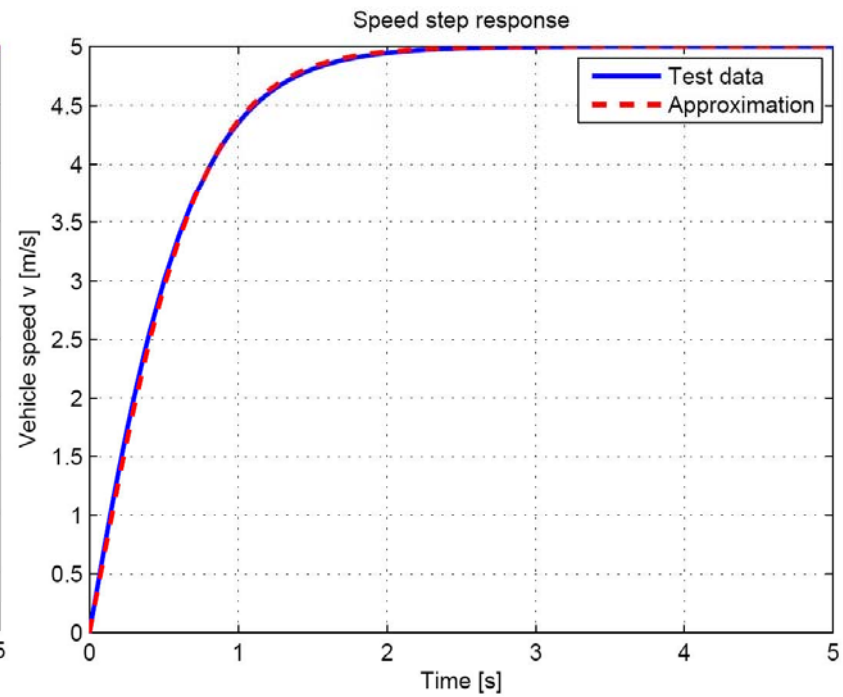
- One way to determine the maximum agility of a vehicle is to record the response of the maneuver states to steps in the control inputs from 0 to 1. Such step-response analysis determines how fast the vessel is able to move in the maneuver space.

# USV Motion Control



- Maneuver map (sixth order fit) and speed step response for the mass-damper system:

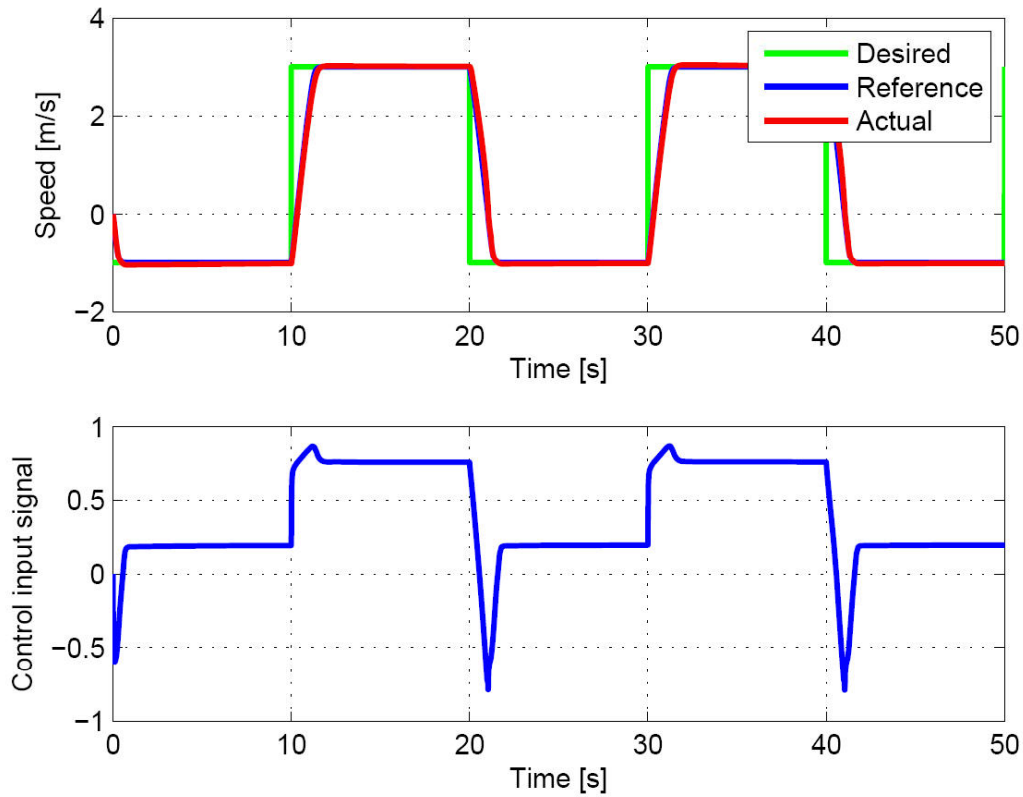


# USV Motion Control



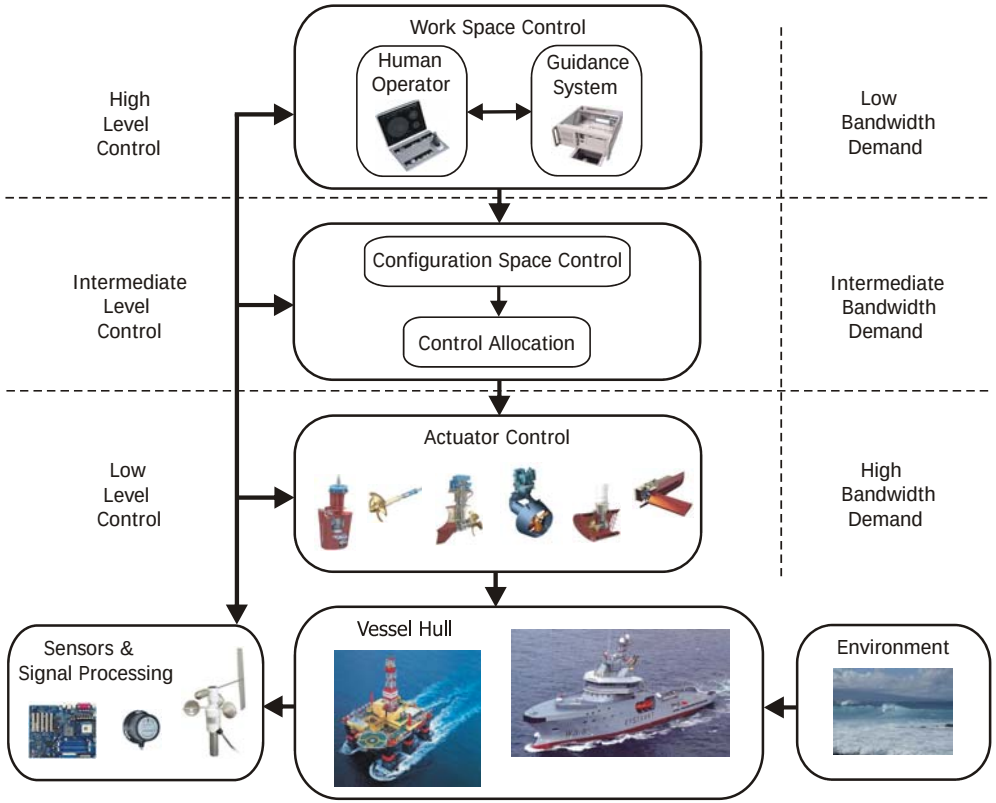
- Simulation results for the mass-damper system:
  - Speed control scenario
  - The desired speed is a square wave with an equillibrium of 1 m/s, an amplitude of 2 m/s and a frequency of 0.5 Hz
  - Also, a disturbance of -10 N was added to the system



# USV Motion Control



- We propose to develop USV throttle and rudder controllers in a similar manner as for the 1D MD system.
- For control of the total horizontal motion, such actuator controllers must be coordinated by a higher level controller that commands feasible work-space references:



# USV Motion Control



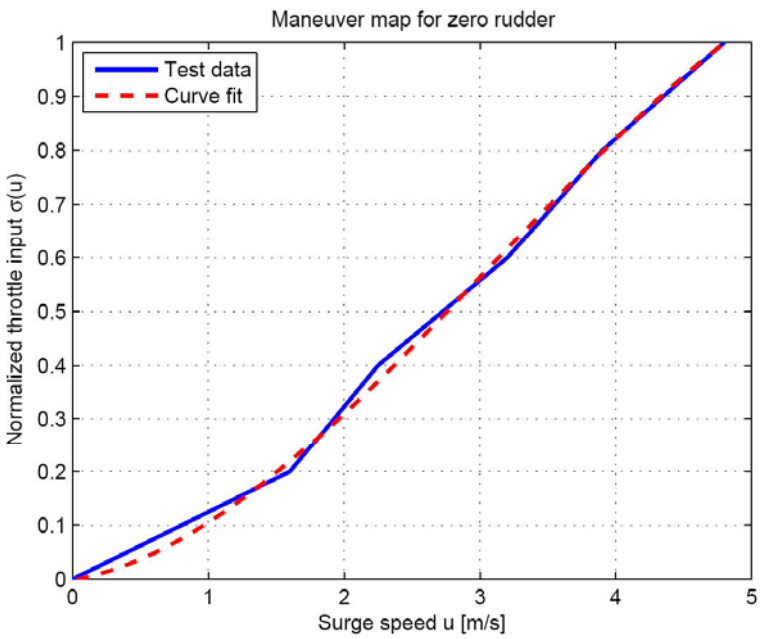
- Full-scale sea trials conducted with the Maritime Robotics Alpha USV:
  - 5.75 m long and 2.12 m wide
  - Evinrude 50 E-Tec outboard engine (corresponds to a propeller and rudder actuator setup)
  - Kongsberg Seapath 20 NAV (with GPS Compass)

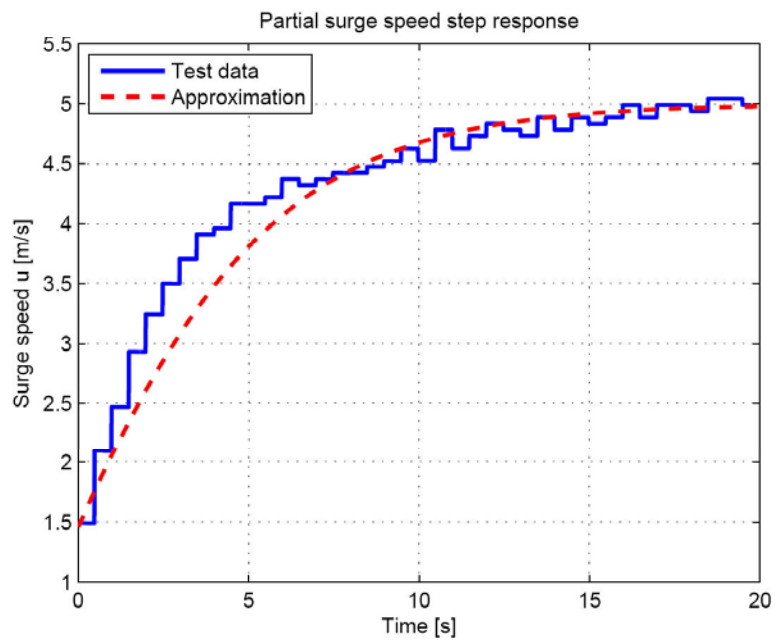

# USV Motion Control



- Rapid prototyping environment with Matlab/Simulink-compliant software.

- Maneuver map (third order fit) and speed step response:

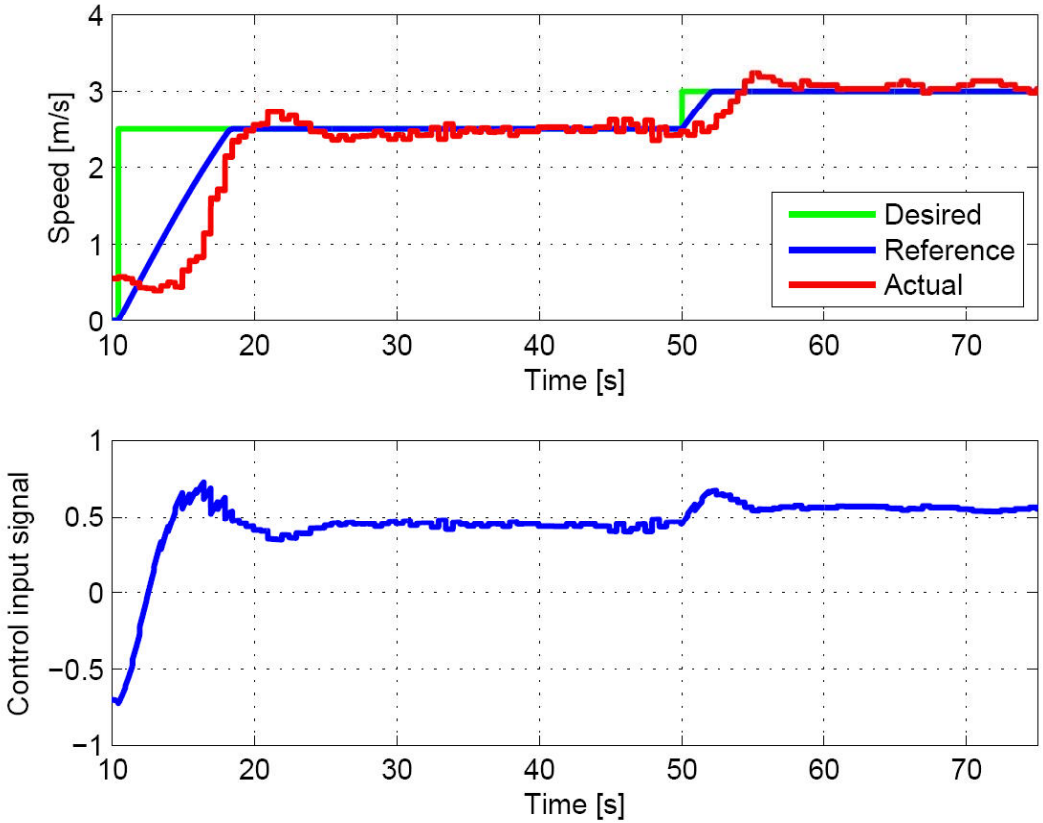


# USV Motion Control



- Full-scale preliminary speed control results:
  - The desired surge speed is first given as a step from 0 m/s to 2.5 m/s and later from 2.5 m/s to 3 m/s
  - The initial surge speed of the USV is 0.55 m/s



# USV Formation Control



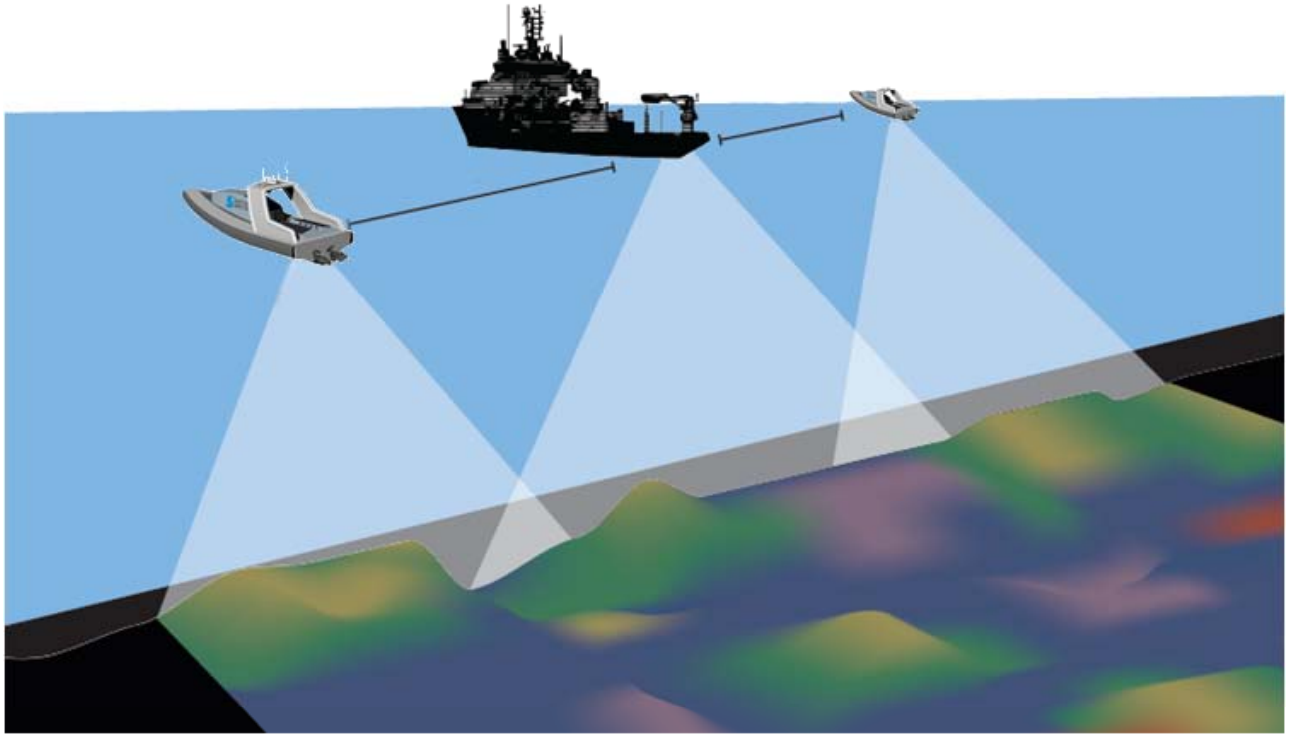
- Motivation includes surveillance of the Barents Sea:


- Provide users with historical and real-time information about what goes on in the ocean space.
- Efficient tool for knowledge-based management of environmental and marine resources.

# USV Formation Control



- Main motivation currently involve offshore survey activity:



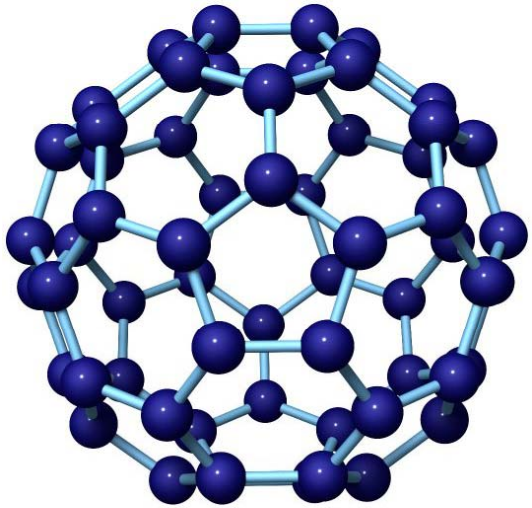
- Augment the capability of the main survey vessel (leader) with a fleet of USVs (followers) that increase the spatio-temporal capacity and reduce operational costs.

# USV Formation Control



- With the survey application in mind, consider the following candidate formation control frameworks:
  - Leader Follower (analytic)
  - Virtual Structure (analytic)
  - Behavioral (algorithmic)

| | | | | |
|---|---|---|---|---|
| 4 | 2 | 2 | 1 | 1 |
| 2 | 3 | 3 | 2 | 1 |
| 2 | 2 | 3 | 1 | 1 |
| 1 | 2 | 1 | 2 | 1 |
| 1 | 3 | 3 | 1 | 1 |



# USV Formation Control



- Choose to consider the leader-follower framework since:
  - The virtual structure framework is poorly suited to underactuated vehicles
  - The performance of the behavioral framework is hard to verify analytically (emergent behavior that must be determined empirically)
  - The framework is well suited to underactuated vehicles (e.g., both underactuated leader and follower vehicles)
- The operation should continue even if a USV experiences failure, i.e., the leader vessel should not adjust its motion according to the weakest link in the formation (which nominally should be itself). However, all followers should adjust to any off-nominal leader behavior
- Hence, we do in fact recommend a set of individual target-tracking scenarios (one for each follower USV)
- Consequently, the only formation intelligence lies in the specification of the formation geometry relative to the leader (apriori coordination)

# USV Formation Control



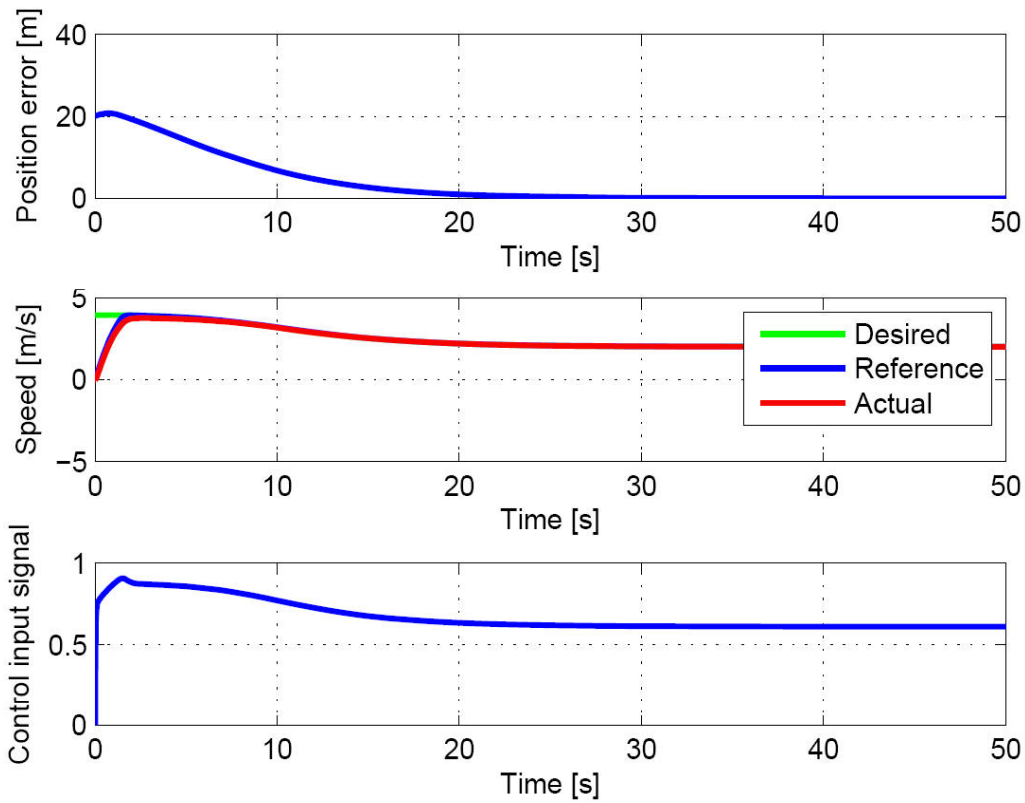
- Practical formation control considerations:
  - Important to specify an initialization (startup) procedure that efficiently and safely achieves formation assembly
  - Likewise, it is important to specify a termination (shutdown) procedure that results in formation dispersion
  - Such procedures are particularly important when involving unmanned vessels that lack certain autonomy-enabling functionality (like, e.g., collision avoidance)

- Example:
  - Unload USVs from their container vessel
  - The unmanned follower vessels are manually controlled until their position and velocity satisfy some formation assembly requirements (relative to the leader position and velocity), at which point their motion control becomes automatic (autonomous)
  - The unmanned follower vessels are brought under manual control when the survey ends and loaded back onto their container vessel

# USV Formation Control



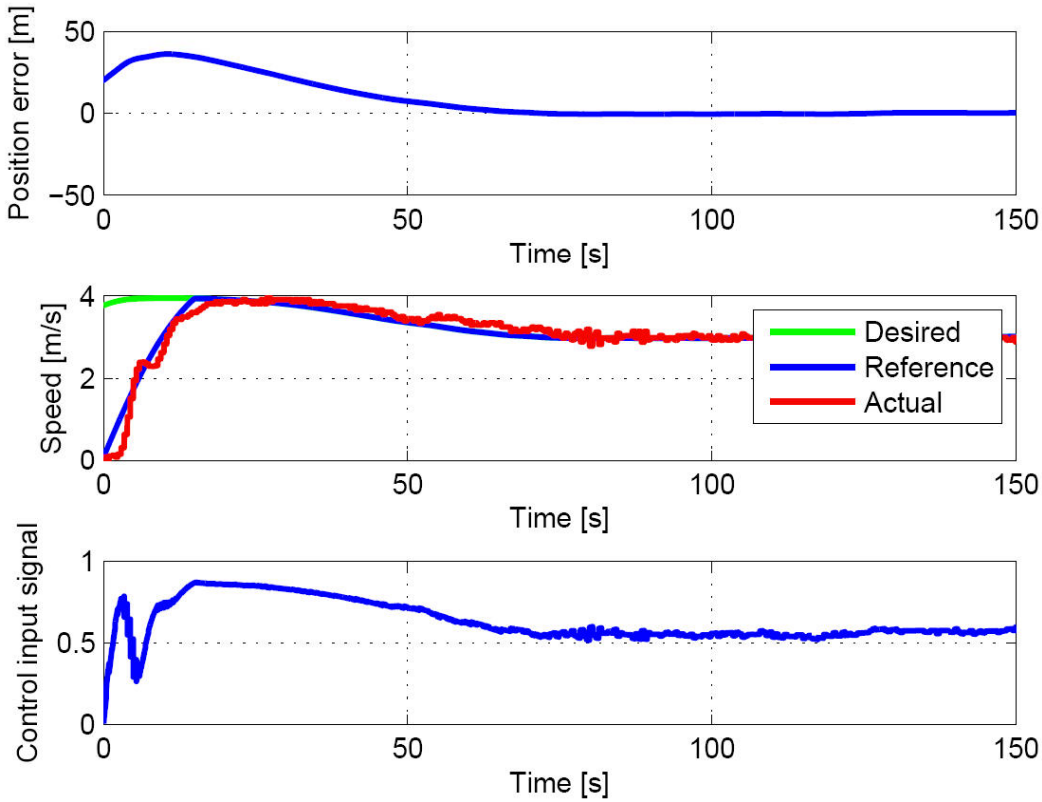
- Simulation results for the mass-damper system:
  - Target tracking
  - The target moves at 2 m/s and starts 20 m ahead of the USV
  - The USV is allowed a maximum approach speed of 2 m/s



# USV Formation Control



- Full-scale sea trials conducted with the Maritime Robotics Alpha USV (preliminary test results):
  - Target tracking along a straight line
  - The target moves at 3 m/s and starts 20 m ahead of the USV
  - The USV is allowed a maximum approach speed of 1 m/s



# USV Formation Control



- Plan to conduct formation control experiments in the Trondheimsfjord during the autumn of 2008:
  - Leader: NTNU's research vessel FF Gunnerus
  - Followers: Maritime Robotics' USVs

# Future Challenges



- A great potential exists for future development of USV technology.
- Facilitating components such as actuators, communications, computers, materials, and sensors are continually being developed.
- In the short term, remotely or semi-autonomous USVs will continue to dominate. For such applications, communications issues are of the utmost importance.
- A shift toward more autonomy will require the introduction of new, advanced motion control concepts, where perhaps the most important contributor is collision avoidance.

# Future Challenges



- Formation control involving completely autonomous members require collision avoidance capabilities (i.e., avoid collisions with both static and dynamic objects).

- Collision avoidance requires both sense and avoid abilities:
  - Sense: Access to both global (ECDIS, AIS, etc.) and local (radar, stereo vision, etc.) information about the environment
  - Avoid: Superior maneuverability and agility through powerful actuators

- The problem is in general still open, and 100% collision avoidance can only be achieved given certain simplifying assumptions. In practice, the capability must probably be evaluated by statistical means.

# Conclusions



- There is a saying along the lines of: "In theory, theory and practice are the same, but not in practice."
- In practice, we require a simple and robust formation control system that performs well for offshore survey applications.
- We choose to place most of the responsibility for the formation control performance on the individual USVs and their motion control systems (target tracking, collision avoidance).
- The prosperity of commercial USV technology in large part relies on the development of a legal framework that regulates the use of unmanned vehicles at sea.
- The development of such a framework is just a question of time, and so the future is surely unmanned!