Aquabots VIP Course
Lecture 2
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UUV Technology Developments

**Improved Navigation**
- Low power INUs for UUVs
- USBL Navigation
- Robust DVL/ADCP

- Low Power Navigation
- FBN

**Platform Improvements**
- Net Cutting
- Autonomous Recovery
- Forward Fin Module
- Hovering Module
- Anchor Module
- Ballast Module
- Payload Delivery Modules

**Control & Autonomy**
- UUV JAUS Standards
- ASTM F41 Architecture
- Hierarchy Autonomy
- Behavior Autonomy
- Obstacle Avoidance
- Onboard CAD/CAC
- Anti-Tamper
- CfN Mission Planning
- Precision Positioning

**Launch & Recovery**
- USV L&R
- Autonomous RHIB L&R
- Ship L&R
- Submerged L&R / Docking Station

**Modularity**
- Standard Interfaces
- Flooded or Dry Payload Sections
- Expandable Payloads

**Communications**
- Acoustic Comms
- Fast RF Comms

**Sensors**
- Marine Sonics DF Sidescan
- EdgeTech Sidescan
- SSAM DF
- RTG / LSG
- ASW
- ATLAS FLS
- LF sensors
- Video w/LED Bar
- Blazed Array Sensors
- Environmental Sensors
- Chemical Sensors
- BOSS

**Propulsion**
- Low Noise & Power Motors

**Power Systems**
- Li Ion Batteries
- Safe Pressure Tolerant Li Ion Batteries
- High Endurance Power Tow Module
UUV Functional Subsystems and Interfaces (ASTM F-41)

- Vehicle Control
  - Mobility/Maneuver
  - Energy
  - Navigation
  - Hardware safety
  - Battery system
  - Navigation system
  - Autopilot
  - Variable ballast
  - Propulsion
  - Effectors

- Autonomous Control
  - SA
  - Planning
  - Functional I/F
  - Situational Awareness
  - Sortie Monitoring
  - Sortie Planning
  - Path Planning
  - Payload Planning
  - Sortie Execution

- Communications
  - Sortie Orders
  - SSF/SSS
  - Offboard queries
  - Comms mgmt
  - ACOMM system
  - RF comm system
  - C2/SSN comm

- Payload Control
  - Payload Control
  - Payload Status
  - Contact Data
  - FLS
  - SLS/SAS
  - ISR
  - ISR Mast
Functional Allocation of Major UUV Autonomy and Control Components (ASTM-F41)
Navigation System: In the broad sense, navigation is the process of monitoring and controlling the movement of a craft or vehicle from one place to another. For a UUV, navigation can be defined as the process of data acquisition, data analysis, and extraction and inference of information about the vehicle’s states and its surrounding environment with the objective of accomplishing assigned missions successfully and safely.
Sensing: A sensing system involves one or a group of devices (sensors) that respond to a specific physical phenomenon or stimulus and generate signals that reflect some features or information about an object or a physical phenomenon. Sensors such as gyroscopes, accelerometers, magnetometers, static and dynamic pressure sensors, cameras and Sonars are commonly used onboard UUVs to provide raw measurements for state estimation and perception algorithms.

State Estimation: This concerns mainly the processing of sensor raw measurements to estimate the different variables that are related to the vehicle’s state, particularly those related to its pose and motion such as attitude, position, velocity, etc. These estimates can be absolute or relative. Localization is a particular case of state estimation which is limited to position estimation relative to some map or other locations.

Perception: UUV perception is its capability to use inputs from sensors to build an internal model of the environment within which it is operating, and to assign entities, events, and situations perceived in the environment to classes. The classification (or recognition) process involves comparing what it observed with the UUV a priori knowledge. Perception can be further divided into various functions of different levels such as mapping, obstacle and target detection, object recognition, etc.

Situational Awareness (SA): SA notion is commonly used in unmanned systems and numerous definitions of SA have been proposed. The perception of elements in the environment within a desirable volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. SA therefore is higher than perception because it requires the comprehension of the situation and then extrapolation or projection of this information forward in time to determine how it will affect future states of the operational environment.
Guidance System (GS)

- Guidance System: A guidance system can be defined as the "driver" of a UUV that exercises planning and decision-making functions to achieve assigned missions or goals. The role of a guidance system for UUV is to replace the cognitive process of a human pilot and operator. It takes inputs from the navigation system and uses targeting information (mission goals) to make appropriate decisions at its high-level and to generate reference trajectories and commands for the low-level control. GS decisions can also spark requests to the navigation system for new information. A guidance system comprises various autonomy enabling functions including trajectory generation, path planning, mission planning, reasoning and high-level decision-making, etc.
Trajectory Generation: a trajectory generator has the role of computing different motion functions (reference position, reference heading, etc.) that are physically possible, satisfy UUV dynamics and constraints, and can be directly used as reference trajectories for the flight controller. Reference trajectories can be pre-programmed, uploaded, or generated in real-time onboard the UUV (dynamic trajectory generation) according to the outputs of higher-level guidance modules.

Path Planning: It can be defined as the process of using accumulated navigation data and a priori information to allow the UUV to find the best and safest way to reach a goal position/configuration or to achieve a specific task. Dynamic path planning refers to onboard, real-time path planning.

Mission Planning: The process of generating tactical goals, a route (general or specific), commanding structure, coordination, and timing for a UUV or a team of unmanned systems. The mission plans can be generated either in advance or in real-time. They can be generated by operators or by the onboard software systems in either centralized or distributed ways. The term dynamic mission planning can also be used to refer to onboard, real-time mission planning.

Decision-Making: Decision-making is the UUV ability to select a course of actions and choices among several alternative scenarios based on available analysis and information. The reached decisions are relevant to achieving assigned missions efficiently and safely. Decision-making process can differ in type and complexity, ranging from low-level decision-making (e.g., fly home if the communication link is lost) to high-level decision-making. Trajectory generation, path planning and mission planning involve also some decision-making processes.

Reasoning and Cognizance: UUV’s ability to analyze and reason using contextual associations between different entities. The highest level autonomy can perform with varying levels of augmentation or replacement of human cognitive process.
Environmental Complexity
- Increased complexity in:
  - Terrain/bathymetry variation
  - Object frequency, density, intent
  - Weather variations
  - Mobility constraints
  - Communication dependencies

Mission Complexity
- Subtasks, decision making
- Organization, collaboration
- Performance
- Vehicle knowledge requirements

Human Interaction
- Type of operators/users (workload, skill levels, etc.)
- Frequency, duration, robot initiated interactions
- Decreased level of situational awareness

Current Gliders and MCM UUVs

LD UUV Littoral Missions

World Ocean Traffic

Littoral Traffic Density

NIST ALFUS
# Levels of Autonomy (DHS)

<table>
<thead>
<tr>
<th>Level</th>
<th>Level Description</th>
<th>Observation Perception/Situation Awareness</th>
<th>Decision Making</th>
<th>Capability</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remote Control</td>
<td>Remote camera images viewed by operator</td>
<td>None</td>
<td>Remote operation in relatively simple stationary environments</td>
<td>Basic teleoperation</td>
</tr>
<tr>
<td>2</td>
<td>Remote Control w/vehicle State Knowledge</td>
<td>Local pose, dash-board sensors, and depth image display for operator</td>
<td>Basic health and vehicle state reporting</td>
<td>Remote operation in relatively complex stationary environments</td>
<td>Teleoperate with operator knowledge of geometry of environment</td>
</tr>
<tr>
<td>3</td>
<td>Pre-Planned mission or retro-traverse</td>
<td>INS/GPS waypoints, collision avoidance</td>
<td>ANS commanded steering based on planned path</td>
<td>Basic path following with operator help</td>
<td>Pre-planned path, retro-traverse, or operator waypoint selection</td>
</tr>
<tr>
<td>4</td>
<td>On-board processing of sensory images</td>
<td>Perception of simple surfaces and shapes</td>
<td>Negotiation of simple environment</td>
<td>Robust leader follower with operator help</td>
<td>Follow foot soldiers on road march or easy cross-country</td>
</tr>
<tr>
<td>5</td>
<td>Simple obstacle detection and avoidance</td>
<td>Local perception and map database</td>
<td>Real-time path planning based on hazard estimation</td>
<td>Basic cross country semi-autonomous navigation</td>
<td>Cross country with frequent operator intervention</td>
</tr>
<tr>
<td>6</td>
<td>Complex obstacle detection and avoidance, terrain analysis</td>
<td>Perception and world model representation of local environment</td>
<td>Planning and negotiation of complex terrain and objects</td>
<td>Cross country with obstacle negotiation with some operator help</td>
<td>Cross country in complex terrain with limited intervention</td>
</tr>
<tr>
<td>7</td>
<td>Moving object detection and tracking, on-road and off-road autonomous driving</td>
<td>Local Sensor fusion with a priori maps of road network, representation of moving objects</td>
<td>Robust Planning and Negotiation of Complex Terrain, Environmental Conditions, hazards and objects</td>
<td>Cross country with obstacle avoidance with little operator help</td>
<td>Cross country in complex terrain with full mobility speed with limited intervention</td>
</tr>
<tr>
<td>8</td>
<td>Cooperative operations, convoy, intersections, on-coming traffic</td>
<td>Real-time fusion of data from external sources, broad knowledge of rules of the road</td>
<td>Advanced decisions based on shared data from other similar vehicles</td>
<td>Rapid effective execution of on-road driving tasks with minimal operator input</td>
<td>On-road operations under normal road conditions with little supervision</td>
</tr>
<tr>
<td>9</td>
<td>Collaborative operation, traffic signs and signals, near human levels of driving skill</td>
<td>Perception in bad weather and difficult environmental conditions</td>
<td>Collaborative reasoning for cooperative tactical behaviors</td>
<td>Accomplish complex collaborative missions with some operator oversight</td>
<td>Effective combat mission accomplishment with little supervision</td>
</tr>
<tr>
<td>10</td>
<td>Full autonomy with human levels of performance or better</td>
<td>Data fusion from all participating battlefield assets</td>
<td>Total independence to plan and implement to meet defined objectives</td>
<td>Accomplish complex collaborative missions with no operator intervention</td>
<td>Fully autonomous combat missions accomplished with results equal to or better than with human intervention</td>
</tr>
<tr>
<td>Level</td>
<td>Level Descriptor</td>
<td>Guidance</td>
<td>Navigation</td>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>----------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>10</td>
<td>Fully Autonomous</td>
<td>Human-level decision-making, accomplishment of most missions without any intervention from ES (100% ESI), cognizant of all within the operation range.</td>
<td>Human-like navigation capabilities for most missions, fast SA that outperforms human SA in extremely complex environments and situations.</td>
<td>Same or better control performance as for a piloted aircraft in the same situation and conditions.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Swarm Cognition and Group Decision Making</td>
<td>Distributed strategic group planning, selection of strategic goals, mission execution with no supervisory assistance, negotiating with team members and ES.</td>
<td>Long track awareness of very complex environments and situations, inference and anticipation of other agents intents and strategies, high-level team SA.</td>
<td>Ability to choose the appropriate control architecture based on the understanding of the current situation/context and future consequences.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Situational Awareness and Cognizance</td>
<td>Reasoning and higher level strategic decision-making, strategic mission planning, most of supervision by RUAS, choose strategic goals, cognizance.</td>
<td>Conscious knowledge of complex environments and situations, inference of self/others intent, anticipation of near-future events and consequences (high fidelity SA).</td>
<td>Ability to change or switch between different control strategies based on the understanding of the current situation/context and future consequences.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>RT Collaborative Mission Planning</td>
<td>Collaborative mission planning and execution, evaluation and optimization of multi-vehicle mission performance, allocation of tactical tasks to each agent.</td>
<td>Combination of capabilities in levels 5 and 6 in highly complex, adversarial and uncertain environment, collaborative mid fidelity SA.</td>
<td>Same as in previous levels (no-additional control capabilities are required).</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Dynamic Mission Planning</td>
<td>Reasoning, high-level decision making, mission driven decisions, high adaptation to mission changes, tactical task allocation, execution monitoring.</td>
<td>Higher-level of perception to recognize and classify detected objects/events and to infer some of their attributes, mid fidelity SA.</td>
<td>Same as in previous levels (no-additional control capabilities are required).</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>RT Cooperative Navigation and Path Planning</td>
<td>Collision avoidance, cooperative path planning and execution to meet common goals, swarm or group optimization.</td>
<td>Relative navigation between RUAS, cooperative perception, data sharing, collision detection, shared low fidelity SA.</td>
<td>Distributed or centralised flight control architectures, coordinated maneuvers.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Obstacle/Event Detection and Path Planning</td>
<td>Hazard avoidance, RT path planning and re-planning, event driven decisions, robust response to mission changes.</td>
<td>Perception capabilities for obstacle, risk, target and environment changes detection, RT mapping (optional), low fidelity SA.</td>
<td>Accurate and robust 3D trajectory tracking capability is desired.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fault/Event Adaptive RUAS</td>
<td>Health diagnosis, limited adaptation, onboard conservative and low-level decisions, execution of pre-programmed tasks.</td>
<td>Most health and status sensing by the RUAS, detection of hardware and software faults.</td>
<td>Robust flight controller, reconfigurable or adaptive control to compensate for most failures, mission and environment changes.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>ESI Navigation (e.g., Non-GPS)</td>
<td>Same as in Level 1</td>
<td>All sensing and state estimation by the RUAS (no ES such as GPS), all perception and situational awareness by the human operator.</td>
<td>Same as in Level 1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Automatic Flight Control</td>
<td>Pre-programmed or uploaded flight plans (waypoints, reference trajectories, etc.), all analyzing, planning and decision-making by ES.</td>
<td>Most sensing and state estimation by the RUAS, all perception and situational awareness by the human operator.</td>
<td>Control commands are computed by the flight control system (automatic control of the RUAS 3D pose).</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Remote Control</td>
<td>All guidance functions are performed by external systems (mainly human pilot or operator).</td>
<td>Sensing may be performed by the RUAS, all data is processed and analyzed by an external system (mainly human).</td>
<td>Control commands are given by a remote ES (mainly human).</td>
<td></td>
</tr>
</tbody>
</table>
Control System

- Control System: Generates the appropriate actuator commands.

Main Functions

- Controller: Generates force settings (ie. desired control action).
- Control allocation: Translate virtual forces into actuator commands (RPM, PWR, torque, displacement, other).
Control system design often requires a delicate balance between conflicting objectives. There are three key ingredients for a successful design:

1. Knowledge of the process to be controlled.
2. Understanding of how performance will be assessed.
3. Knowledge of fundamental limitations that may prevent any design from achieving the desired performance: Feasibility and constraints.

Once we know these factors, we can select from the different design methods of control theory the one that best suits our problem!
UUV Control System
Methods for AUV Navigation

- Dead-reckoning
  - magnetic compass
  - inertial navigation systems (INS)
  - Doppler velocity sonar
  - error grows without bound; growth rate a function of $$$
- GPS (global positioning system)
  - available only at the surface
- Acoustic navigation
  - long baseline (LBL) and ultrashort baseline (USBL) transponder arrays
  - transponder deployment and calibration are critical
- Feature-based navigation (aka SLAM)
  - Build and concurrently navigation relative to a map
Why is underwater navigation a hard problem?

Due to the absorption of electromagnetic waves, we cannot rely on:

- GPS
- Laser scanner
- Visually-aided navigation
- Radio communication

State of the art for absolute positioning:

- Triangulation from navigation buoys at known locations
- Surfacing for GPS
What navigation information do we have?

Dead-reckoning:
- Compass + speed est.
  - Error: 10% dist. traveled
- Doppler Velocity Logger
  - Error: 1% dist. traveled
  - Distance < 200 m to bottom or surface
- Inertial Navigation System
  - Error: 0.2% dist. traveled
  - Expensive ($100,000)

Navigation error grows without bound!
Dead-Reckoning (Inertial/Doppler)

- Depth sensor → underwater navigation is a 2D problem
- Compass (price: $1k; accuracy: 1-3 degrees)
- Fiber Optical Gyro (FOG) (price:$40k; accuracy: 0.1 degree)
- Attitude Heading Rate Sensor (AHRS)
- Doppler Velocity Logger (DVL)
  - Speed over ground
  - Maximum distance to seafloor: 30 m – 200 m
- Best case AUV navigation accuracies
  - Surface: GPS
  - Near seafloor: 0.1% distance traveled
  - Mid-water column: 1.5 km/h drift
### Summary of Navigation Sensors


<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>VARIABLE</th>
<th>UPDATE RATE</th>
<th>PRECISION</th>
<th>RANGE</th>
<th>DRIFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Altimeter†</td>
<td>Z - Altitude</td>
<td>varies: 0.1-10Hz</td>
<td>0.01-1.0 m</td>
<td>varies with frequency</td>
<td>—</td>
</tr>
<tr>
<td>Pressure Sensor†</td>
<td>Z - Depth</td>
<td>medium: 1Hz</td>
<td>0.1% - 0.01%</td>
<td>full ocean depth</td>
<td>—</td>
</tr>
<tr>
<td>Inclinometer†</td>
<td>Roll, Pitch</td>
<td>fast: 1-10Hz</td>
<td>0.1° - 1°</td>
<td>+/- 45°</td>
<td>—</td>
</tr>
<tr>
<td>Magnetic Compass‡</td>
<td>Heading</td>
<td>fast: 1-10Hz</td>
<td>1° - 10°</td>
<td>360°</td>
<td>—</td>
</tr>
<tr>
<td>Gyro: (mechanical)†</td>
<td>Heading</td>
<td>fast: 1-10Hz</td>
<td>0.1°</td>
<td>360°</td>
<td>—</td>
</tr>
<tr>
<td>Gyro: Ring-Laser and Fiber-optic‡</td>
<td>Heading</td>
<td>fast: 1-1600Hz</td>
<td>0.1° - 0.01°</td>
<td>360°</td>
<td>0.1° - 10°/h</td>
</tr>
<tr>
<td>Gyro: North Seeking‡</td>
<td>Heading, Pitch,</td>
<td>fast: 1-100Hz</td>
<td>0.1° - 0.01°</td>
<td>360°</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Roll, y, ω</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 kHz LBL</td>
<td>XYZ Position</td>
<td>varies: 0.1-1.0 Hz</td>
<td>0.1-10 m</td>
<td>5-10 Km</td>
<td>—</td>
</tr>
<tr>
<td>300 kHz LBL</td>
<td>XYZ Position</td>
<td>varies: 1.0-10.0 Hz</td>
<td>+/-0.007 m</td>
<td>100 m</td>
<td>—</td>
</tr>
<tr>
<td>IMU†</td>
<td>x, ω, ω̇</td>
<td>fast: 1-1000Hz</td>
<td>0.01m</td>
<td>varies</td>
<td>—</td>
</tr>
<tr>
<td>Bottom-Lock Doppler‡</td>
<td>x_{body}</td>
<td>fast: 1-5Hz</td>
<td>0.3% or less</td>
<td>varies: 18 - 100 m</td>
<td>—</td>
</tr>
<tr>
<td>Global Positioning System</td>
<td>XYZ Position</td>
<td>fast: 1-10 Hz</td>
<td>0.1-10 m in air</td>
<td>In water: 0 m</td>
<td>—</td>
</tr>
</tbody>
</table>

† — Internal Sensor