Guidance Systems: The Brains of Motion Control Systems

Dr. Morten Breivik
Centre for Ships and Ocean Structures
Norwegian University of Science and Technology

A Minuteman III missile is launched on a suborbital trajectory toward the Kwajalein Atoll from Vandenberg Air Force Base in California, USA on June 14, 2006. Courtesy of Goleta Air & Space Museum.
Outline

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- Autonomy and Human-Like Cognitive Functionality

References:
- Literature on Guidance and Motion Control

Brave New World:
- Links to Videos and Reports on Norwegian USV Research
A vehicle motion control system involves at least 3 levels of control in a hierarchical structure:
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- **High level control** involves the calculation of motion reference signals which correspond to desired vehicle maneuvers

- The main task of this control level is to solve motion control objectives associated with important motion control scenarios, including:
  - Target tracking (tracking a moving target)
  - Path following (traversing a geometric path)
  - Formation control (cooperation between multiple vehicles)
  - Collision avoidance (avoiding both static and dynamic objects)

- Constituting the strategic level of control, it is essentially the **brain** of all the nested control loops that together make up a vehicle motion control system

- Humans currently participate directly at this level most of the time

- The autonomous part of the strategic level is called the **guidance system**
A vehicle motion control system involves at least 3 levels of control in a hierarchical structure:

- The **intermediate control level** considers how actual vehicle motion can be generated and calculates the forces and moments required to execute the desired maneuvers commanded by the high-level controllers.

- Controllers at this level are typically designed by **model-based methods** and must handle both parametric uncertainties and environmental disturbances.

- The commands issued by these controllers are supplied as reference signals to low-level actuator controllers by means of a distribution scheme known as control allocation.

- Humans often participate directly at this level of control.
Low Level Control

A vehicle motion control system involves at least 3 levels of control in a hierarchical structure:

- **Low level control** is related to the local control of vessel actuators such as tunnel thrusters, azimuth thrusters, water jets, rudders, propellers, etc.
- The controllers at this level ensure that the actuators in fact deliver the forces and moments requested by the intermediate control module and ultimately that the vehicle moves as requested by the guidance system.
- This control level is the tactical level with the **greatest bandwidth demand**.
- Humans usually do not participate directly at this level.
According to Shneydor, guidance is defined as:
“The process for guiding the path of an object towards a given point, which in general may be moving”

Charles Stark Draper, the father of inertial navigation, stated:
“Guidance depends upon fundamental principles and involves devices that are similar for vehicles moving on land, on water, under water, in air, beyond the atmosphere within the gravitational field of earth and in space outside this field”
Guidance

- Consequently, guidance represents a fundamental methodology which transcends particular vehicle applications.

- Guidance is concerned with the transient motion behavior associated with achieving motion control objectives.

- The most rich and mature literature on guidance is typically found within the guided missile community.

- Locke defines a guided missile as:
  
  "A space-traversing unmanned vehicle which carries within itself the means for controlling its flight path."

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Guidance

Guided missiles have been operational since World War II, so organized research on guidance theory has been conducted almost as long as organized research on control theory.

Continuous progress in missile hardware and software technology has made increasingly advanced guidance concepts feasible for implementation.

Today, missile guidance theory encompass:
- Classical guidance laws
- Optimal guidance laws
- Guidance laws based on fuzzy logic and neural network theory
- Differential-geometric guidance laws
- Guidance laws based on differential game theory
Fundamental motion control concepts include:
- Operating spaces
- Actuation properties
- Motion control scenarios

We mainly distinguish between two operating spaces:
- **Work space**: The physical space in which a vehicle moves
- **Configuration space**: Constituted by the set of variables sufficient to specify all points of a rigid-body vehicle in the work space

Each of the variables associated with the configuration of a vehicle is called a degree of freedom (DOF)
We mainly distinguish between two actuation properties:

- **Full actuation**: A fully actuated vehicle is able to independently control all its DOFs simultaneously.
- **Underactuation**: An underactuated vehicle is not able to independently control all its DOFs simultaneously.

A vehicle that is underactuated in its configuration space can still achieve meaningful tasks in its work space. It will however typically lack 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.), forced to maneuver energy-efficiently:

- Ships are typically underactuated above 1.5 - 2 m/s (3 - 4 knots).
Motion control scenarios are traditionally divided into:

- **Point stabilization**: Motion toward a stationary point
- **Trajectory tracking**: Motion along a time-parameterized path
- **Path following**: Motion along a time-independent path
- **Maneuvering**: A mix between trajectory tracking and path following where the time parameterization of the path can be changed dynamically, for example according to the vehicle dynamics

These scenarios are typically defined by motion control objectives which are given as configuration space tasks and are therefore best suited for fully actuated vehicles.

They also typically involve desired motion which has been defined a priori (beforehand) in some sense and do not seem to consider the case where no future motion information is available.

A new classification scheme is therefore suggested which considers both apriori and non-apriori scenarios and where the motion control objectives are given as work space tasks.

Such scenarios cover more broadly and are also suited for underactuated vehicles.
Motion Control Scenarios

- **Target tracking:**
  - The control objective is to track the position of a target which moves such that only its instantaneous motion is known. When the target is stationary, this scenario corresponds to point stabilization.
  - For this scenario, it is impossible to separate the spatio-temporal constraint associated with the target position (to be at a certain position at a certain time) into two separate - spatial and temporal - constraints.

- **Path following:**
  - The control objective is to converge to and follow a predefined geometric path, which only involves a spatial constraint.
  - No restrictions are placed on the temporal propagation along the path.

- **Path tracking:**
  - The control objective is to track the position of a target which is constrained to move along a predefined path, corresponding to the trajectory tracking scenario.
  - For this scenario, it is possible to separate the spatio-temporal constraint of the target position into two separate constraints.
  - By disregarding any a priori path information, this scenario can also be viewed as a target tracking scenario and handled with corresponding methods, although resulting in a strange tracking behavior relative to the path.
Motion Control Scenarios

- **Path maneuvering:**
  - The control objective is to employ knowledge about vehicle maneuverability constraints to feasibly negotiate (or somehow optimize the negotiation of) a predefined path, for instance by traversing the path as fast as possible without derailing at any point.

- Consequently, we either have:
  - **Target tracking**, where only instantaneous (and also historic) information about the target point is available:
  
  ![Target tracking diagram]

  - **Path scenarios**, where the target point traverses a path that is apriori known:

  ![Path scenarios diagram]
Concerning tracking of moving targets, the missile guidance community probably has the most comprehensive experience:

- The object that is supposed to destroy another object is commonly referred to as either a missile, an interceptor or a pursuer
- Conversely, the threatened object is typically called a target or an evader

Here, the neutral designations interceptor and target will be used

An interceptor missile typically undergoes 3 operational phases:
1. Launch (become airborne and acquire steering controllability)
2. Midcourse (only coarse pursuit of the target position)
3. Terminal (achieve accurate intercept of the target position)

In the following, we will consider 3 terminal guidance strategies:
- Line-of-sight (LOS) guidance
- Pure pursuit (PP) guidance
- Constant bearing (CB) guidance
**Target Tracking**

- Line-of-sight (LOS) guidance:
  - 3-point guidance scheme
  - The interceptor must constrain its motion along the line of sight between a specific reference point and the target
  - Similar to pure pursuit guidance when on the LOS path
  - Typically employed for surface-to-air missiles, often mechanized by a ground station which illuminates the target with a beam that the guided missile is supposed to ride (beam-rider guidance)
Target Tracking

Pure pursuit (PP) guidance:
- 2-point guidance scheme
- The interceptor must align its linear velocity along the interceptor-target line of sight
- This strategy is equivalent to a predator chasing a prey in the animal world and very often results in a tail chase
- Typically employed for air-to-surface missiles
Target Tracking

- Constant bearing (CB) guidance:
  - 2-point guidance scheme
  - The interceptor must align the relative interceptor-target velocity along the interceptor-target line of sight
  - Often referred to as parallel navigation (zero LOS rotation rate)
  - Typically employed for air-to-air missiles
  - Used for centuries by mariners to avoid collisions at sea
  - Proportional navigation is the most common implementation method (achieves target intercepts, matching only position)
Target Tracking

- Constant bearing (CB) guidance:
  - Can also be implemented as a direct velocity assignment in order to achieve a target rendezvous (matching both position and speed)

\[ \mathbf{v}_d(t) = \mathbf{v}_t(t) + U_{a,max} \frac{\mathbf{p}(t)}{\sqrt{\mathbf{p}(t)^T \mathbf{p}(t) + \Delta_p^2}} \]

Target Tracking

The full picture:

- In our consideration, guidance laws are thus equivalent with kinematic control laws, which can be given as either:
  - Speed and/or steering laws
  - Direct velocity assignments
Motion camouflage:

- Some predators are able to adjust their movement according to their prey such that the prey perceive them as stationary objects in the environment.
- Such behavior is also reported for mating rituals and territorial disputes, for example involving dragonflies.
- Two types of motion camouflage are mainly employed in nature:
  - Camouflage against an object close by (equivalent to LOS guidance)
  - Camouflage against an object at infinity (equivalent to CB guidance)
- The motion camouflage technique works since some creatures detect the motion component across the object-prey LOS far better than the component along the LOS.
Robotic interception:

- Online optimization methods for time-optimal motion planning for robot manipulators operating in dynamic environments are typically very computationally demanding.
- Computationally simple methods involving proportional navigation have been employed to achieve an intercept between a manipulator end effector (interceptor) and a moving object (target).

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Path Following

- Assuming positive speed, path following basically amounts to assigning suitable steering laws.

- Steering for straight lines:
  - Enclosure-based steering
  - Lookahead-based steering

\[ \chi_r(e) \triangleq \arctan \left( -\frac{e(t)}{\Delta} \right) \]
Path Following

Steering for circles:
- It is important to aim along the path tangential and not along the path itself
- NB: These two alternatives are identical for straight line paths, but not for curved paths
Path Following

- Path following for regularly parameterized paths:
  - Paths that never degenerate into a point nor have sharp corners
  - In this case, a path-constrained collaborator is required to avoid the kinematic singularity associated with the osculating circle

Related to the missile guidance laws, lookahead-based steering can be interpreted as pure pursuit of the lookahead point ("donkey and carrot" analogy)

\[
\dot{\omega} = \frac{U(t) \cos \chi_r(e) + \gamma s(t)}{|p_p'(\omega)|}
\]
Path Following

- The lookahead-based steering law can also be written as:

\[ \chi_r(e) = \arctan(-k_p e(t)) \], \quad k_p = \frac{1}{\Delta} > 0

- The steering law is therefore equal to a saturated proportional control law. It is well known that a small lookahead distance \( \Delta \) implies aggressive steering, which is intuitively confirmed by a correspondingly large proportional gain \( k_p \) in the saturated control interpretation.

- Integral action can also be added into the steering law. Although not required in a purely kinematic setting, an integrator can be useful for vehicles which are under the influence of ocean currents without having access to velocity information:

\[ \chi_r(e) = \arctan \left( -k_p e(t) - k_i \int_0^t e(\tau) d\tau \right) \]

- However, care must be taken to avoid overshoot and windup effects when using integral action in the steering law.
Want to design a motion control system for an underactuated unmanned surface vehicle (USV) with an outboard engine:
For underactuated vehicles, the direction of the vehicle velocity is generally not equal to the vehicle heading.

Therefore, it is important to control the vehicle velocity and not the vehicle heading to achieve the desired motion control objectives.

Velocity-based guidance laws have already been reviewed for target-tracking and path-following motion control scenarios. For underactuated vehicles, direct velocity assignments can be decomposed into speed and steering assignments.
Motion Control Example

Motion control system in the hierarchical interpretation:

**Strategic level:**
- Desired motion \(\rightarrow\) Velocity commands
- Low Bandwidth Demand

**Tactical level:**
- Velocity control \(\rightarrow\) Actuator commands
- Intermediate Bandwidth Demand

**Execution level:**
- Actuator control \(\rightarrow\) Actual motion
- High Bandwidth Demand
Motion Control Example

- **Kaasbøll USV:**
  - **Guidance Law:** Target Tracking or Path Scenario
  - **Polar Coordinate Decomposition:**
    \[ \ddot{U}(t) \rightarrow \ddot{u}(t) \quad \text{and} \quad \ddot{\chi}(t) \rightarrow \ddot{r}(t) \]
  - **Surge Feasibility Filter:** \( \ddot{u}(t) \rightarrow \ddot{u}(t) \)
  - **Surge Speed Controller:** \( \tau_c(u_T(t), \ddot{u}(t)) \)
  - **Yaw Feasibility Filter:** \( \ddot{r}(t) \rightarrow \ddot{r}(t) \)
  - **Yaw Rate Controller:** \( \delta_c(r_T(t), \ddot{r}(t)) \)
  - **Onboard Computer and Outboard Engine**

- **Modular design approach**

- **Lookahead-based steering**
  - Velocity controllers based on any favorite model-based control method
  - Actuators which physically move the vehicle

- **Constant bearing guidance**
Some plots showing the startup and steady state behavior of the Kaasbøll USV during a straight-line target tracking scenario:

In this full-scale experiment, a virtual target moves due north at a speed of 3 m/s (6 knots), while the USV is velocity-controlled using constant bearing guidance to achieve target rendezvous.

Future Challenges

- Current motion control systems make it possible for vehicles to achieve missions which humans carefully specify in advance, like a target-tracking motion control scenario. That is, the vehicles do what most machines can do better than people – provide very high precision in technical operations.

- However, it is not yet possible to give a vehicle’s control computer only approximate orders which it must boil down to something very concrete and practical itself.

- Such cognitive functions represent the next big step in the technology evolution for vehicle guidance systems.
Future Challenges

In the long term it is desirable to develop more advanced cognitive guidance systems which will make the vehicles partly or completely independent of human intervention.

Such autonomous vehicles will be able to make their own decisions in unfamiliar and unstructured environments. However, such abilities will require the boats to be equipped with intelligence similar to humans.

It still remains to clarify whether we humans are so intelligent that we are able to understand our own intelligence and thus reproduce it artificially. If not, we will probably never witness truly autonomous vehicles, only bleak copies of our own capabilities.
A shift toward more autonomy will require a gradual introduction of increasingly advanced motion control functionality.

In the short term, one of the most important functionalities is collision avoidance, which requires both sense and avoid abilities:

- **Sense**: Access to both global (electronic charts, etc.) and local (radar, stereo vision, etc.) information about the surrounding environment.
- **Avoid**: Superior maneuverability through powerful actuators, as well as advanced motion control algorithms capable of performing both long-term (proactive) and short-term (reactive) planning to ensure avoidance.

The main challenge in making practical use of a collision avoidance system lies in the sensor solutions. A composite sensor package which can be trusted to detect both large and small objects in all types of visibility and weather conditions must be developed.
Future Challenges

- We basically want to develop unmanned and autonomous vehicles like:

- We are currently at the beginning of a technological development which will turn many things upside down. Incredible research challenges exist within the area of advanced guidance systems for unmanned and autonomous vehicles.
Some relevant references on guidance systems and motion control:

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As inspiration for a new breed of control engineers developing the next generation of advanced cognitive guidance systems for use in unmanned and autonomous vehicles, the following media-related material may be useful:

- NRK Schrödingers Katt feature on Pilotless Boats
- Research magazine Gemini report on Autonomous Robots at Sea
- YouTube video on USV Formation Control in the Trondheimsfjord