Navigation and Guidance

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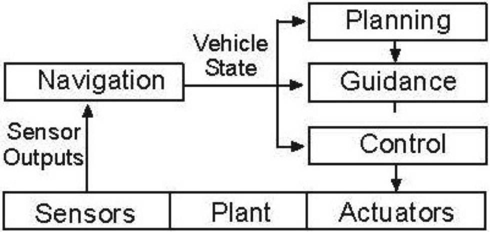
Objective of Course

- To familiarize the students with different types of navigation methods used for aerospace applications
- To provide exposure of various guidance strategies (classical as well as modern) to guide the aerospace vehicle for a desired mission.

- **Flight Planning**: Determination of a nominal flight path and associated control histories for a given flight vehicle to accomplish specified objectives with specified constraints.
- **Navigation**: Determination of a strategy for estimating the position of a vehicle along the flight path, given outputs from specified sensors.
- **Guidance**: Determination of a strategy for following the nominal path in the presence of off-nominal conditions, wind disturbances, and navigational uncertainties.
- **Control**: Determination of a strategy for maintaining the angular orientation of the vehicle during the flight, that is consistent with the guidance strategy and the vehicle constraints.

Bryson, A. E., “New Concepts in Control Theory, 1959-1984”, *Journal of Guidance, Control and Dynamics*, Vol. 8, No. 4, 1985, pp. 417-425.

- Navigation may have one of two meanings.
  - ⇒ Accurate determination of the vehicle state (e.g., position, velocity, and attitude);
  - ⇒ Planning and execution of the maneuvers necessary to move between desired locations.



- Whenever a purposeful change in location has to take place for an aircraft the following questions must be asked and answered:
  - ⇒ Where is the aircraft now?
  - ⇒ More specifically, where is the aircraft now with respect to where it should have been?

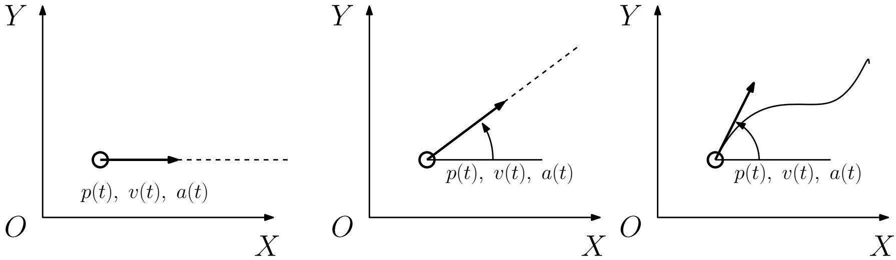
- Reasons for sophisticated navigation systems
  - ⇒ Time lags between measurement and decision needs to be reduced.
  - ⇒ Number of aircraft in a given airspace has increased in the past few decades.
  - ⇒ Safety requirements have become crucial.

- A classical approach to vehicle state estimation is to equip the vehicle with inertial sensors capable of measuring vehicles's acceleration and angular rate.
- With proper calibration and initialization
  - $\Rightarrow$ Integration of the angular rates provides an estimate of the attitude
  - $\Rightarrow$ Integration of acceleration provides estimates of velocity and position
- Any possible issue or benefit of integration?
- Integration will perform smoothening of high-frequency errors (e.g., sensor noise)
- Integration of low frequency errors due to biases, scale factor error, or misalignment will cause increasing error between the true and estimated vehicle state.

- Consider a point moving in a plane.
- Kinematic Model:

$$\begin{aligned}\dot{p}(t) &= v(t) \\ \dot{v}(t) &= a(t)\end{aligned}$$

where, $p(t),\ v(t),\ a(t)$ denote position, velocity, and acceleration, respectively.



- **Navigation**: Art of directing the movement of vehicle from one point on Earth or space to another point.
- Historically, types of navigation:
  - ⇒ Celestial navigation: Present position is computed by measuring the elevation angles or altitudes of stars and noting the time of observation.
  - ⇒ Dead reckoning: Course and distance traveled from the point of departure are maintained by plotting on a chart, or by continuous computation of north-south and east-west components from the heading and the speed of the vehicle.
  - ⇒ Piloting: Landmarks or beacons and the visual pattern on the Earth's surface are used, as for taking a ship into port.
- Navigation problem
  - ⇒ Where am I?⇒ Position
  - ⇒ How fast am I going?⇒ Speed
  - ⇒ In which direction we are moving?⇒ Heading/Direction
  - ⇒ How far is it from my destination?⇒ Distance-to-go

- Modern aircraft are of high speed and flying at high altitude.
- Radio and radar navigation are useful for providing position, direction, and average velocity.
  - ⇒ Susceptible to weather conditions and electromagnetic interference
- Inertial navigation system (INS) overcomes this issue. How?
  - ⇒ Do not require external device or signal
  - ⇒ Provide position, ground speed, true heading, distance-to-go, and relative bearing to destination in convenient coordinate system
- Integration of INS with additional non-inertial navigation equipments or sensors
  - ⇒ A precise reference on a continuous basis with external data being used to periodically update the system.
- Why is this integration required?

- INS outputs may not be exact due to many reasons.
  - ⇒ Presence of inertial sensor (i.e., gyroscopes and accelerometers) inaccuracies
  - ⇒ Error due to gravity modeling
- These system error sources drive the system errors, causing unbounded velocity, position, and attitude errors.
- Within a short period of time, the navigation system errors become excessive for the majority of missions.
- Specifically, INS errors grow with time in the free inertial mode.
- Auxiliary information from noninertial external sensors avoids error's growth.
- In general, the errors in the noninertial sensors do not increase with time.
- System errors can be bounded and reduced by use of
  - ⇒ High-quality inertial sensors
  - ⇒ A good gravity model
  - ⇒ Noninertial (i.e., redundant) sensors

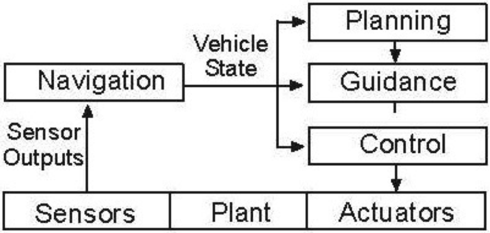
- Navigation systems wherein low rate sensors are used to correct the state estimate produced by integration of the outputs from high rate sensors are referred to as aided or integrated navigation systems.
- Aided navigation involves two categories of sensors.
- Output signals from sensors in the first category are integrated using a kinematic model of the system.
  - ⇒ Result of this integration provides a reference trajectory.
  - ⇒ Example: Kinematic input sensors include inertial measurement units, Doppler radar or sonar, etc.
- Elements of the second category of sensors are used to estimate the error between this reference trajectory and trajectory of the vehicle.
- Mixing of information from these sensors with INS information
  - ⇒ Combination of short-term accuracy of inertial instruments and the long-term accuracy of non-inertial (NAVAID) sensors.

- Accuracy of any inertial navigation system
  - ⇒ Initial condition
  - ⇒ Alignment of sensors
  - ⇒ Present position coordinates and headings
- **Gyroscope**: Heart of INS
- System performance depends on ability of gyroscope to provide a precision inertial reference frame.
- **Accelerometer**: To measure components of specific force in a reference frame defined by gyroscopes.
- INS have the ability to maintain a reference frame in which the combined effects of inertial acceleration and gravity are resolved.
- Key components of INS
  - ⇒ Coordinate frames
  - ⇒ Gyroscope
  - ⇒ Accelerometer

Navigation System

- The navigation system functions to provide position, velocity, and attitude of the vehicle with respect to a reference coordinate frame.
- Using high-accuracy gyros and accelerometers, it is conventionally configured as an inertial system in either a gimballed or strapdown mode.

- **Guidance**: Process for guiding the path of an object towards a given point, which in general may be moving.
- **Guidance system**: Brain of an aerospace vehicle
- Generation of the guidance commands to achieve desired objectives of aerospace vehicle.
- It utilizes the vehicle's current states and their deviations from desired values to nullify the errors in controlled variables.



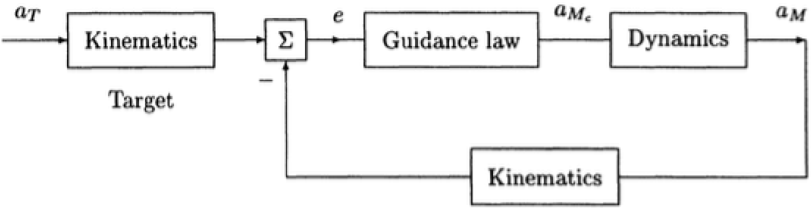


Figure: Guidance loop

- Error e is a function of the deviation of pursuer's state in space and their desired values.
- In most of the cases for vehicle with aerodynamic control, the guidance command is lateral acceleration of vehicle.

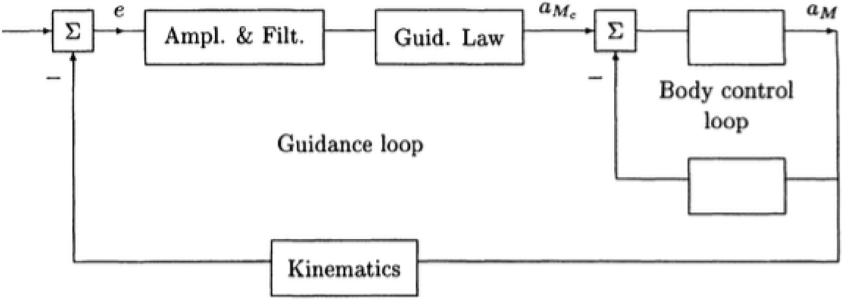
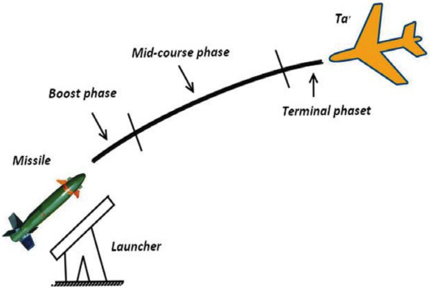
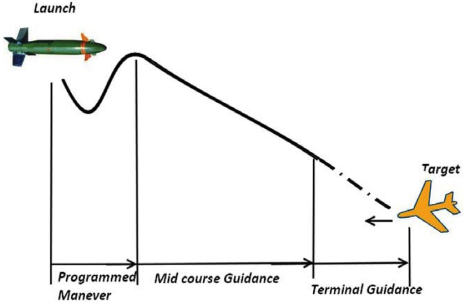


Figure: Body control loop within guidance loop

- Inner loop is body control loop.
- It is usually faster than the guidance loop.
- For many applications, it is assumed to have zero order dynamics.



(a) Surface-to-Air Missiles



(b) Air-to-Air Missiles

Guidance system: Missile applications

- To find the appropriate compensation network to place in series with the plant in order to accomplish an intercept.
- Based on the principles of feedback control, to impact a maneuverable target with little miss distance.
- To determine appropriate pursuer flight path dynamics such that some pursuer objective might be achieved efficiently.
- To decide the best trajectory (physical action) for the pursuer based on its knowledge of the capabilities of pursuer and target, and desired objectives.
- Guidance computer mathematically integrate the separate functions of navigation and the flight control system.
- In many applications, the guidance system is designed so that it makes use of an inertially stabilized tracker (for example, seeker) that directly measures the angular rates between the pursuer and its target in a fixed coordinate frame.

Flight Control System (FCS):

- The function of Flight Control System (FCS) is to control the pursuer in pitch, yaw, and roll motion.
- The FCS executes the guidance commands and stabilizes the pursuer in flight.
- The FCS, upon receiving commands from the guidance law, issues its own commands to the appropriate aerodynamic and/or thrust controls of the pursuer so that the guidance command can be properly executed.

References

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3. N. A. Shneydor, *Missile Guidance and Pursuit: Kinematics, Dynamics and Control*, Woodhead Publishing, 1998.