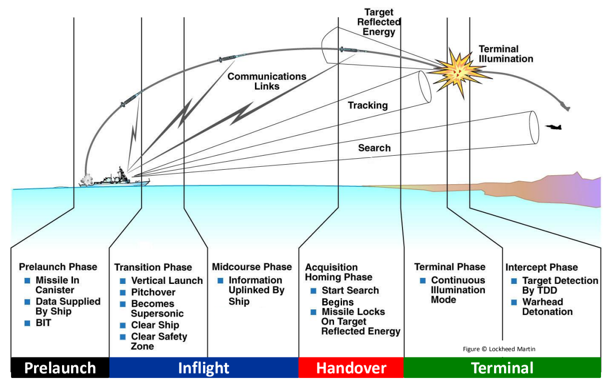
Principles of Weapon Control Systems II

Gregg Bock

Missile Engagement Sequence



WCS Responsibilities

Previous Lecture

Pre-Firing Decision (Prelaunch) Processing
- Intercept Prediction
- Determining Weapon Capability
- Scheduling Weapon Selection
- Weapon initialization

Post Intercept Processing
- Engagement Evaluation
- Kill Assessment

Post-Firing Decision (Inflight) Processing
- Guidance & Control
- Handover support
- Track the Weapon
- Engagement Monitoring

Support Functionality
- Track Processing (filtering)
- Resource Management
- Scheduling
- Displays

Inflight Processing

- The complexity of inflight processing varies greatly from system to system or weapon to weapon
- Guidance & Control
  - Intelligent weapons compute guidance commands to steer the interceptor to the target
  - The weapon or WCS may use additional information to alter the manner in which the weapon operates
  - The weapon system requires an estimate of the intercept event to determine **when** and **where** the intercept will occur and/or produce guidance commands
- Handover support
  - Ensure the weapon is provided with the information and resources needed to complete the engagement
    - Target cueing information
    - Additional resources / information required for terminal guidance (illuminators, etc.)
- Track the weapon
  - Not all weapons are tracked
  - Some weapons have a complex feedback loop with the weapon system that requires tracking
- Engagement monitoring
  - Evaluate progress of the engagement

Guidance
Weapon Guidance & Control

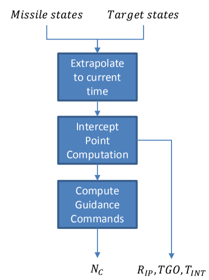
- Used to generate commands used to control the interceptor's trajectory
- Three phases of guidance
  - Terminal
    - Provides acceleration commands through intercept
  - Midcourse
    - Provides acceleration commands until the terminal guidance begins
  - Initial
    - Stabilizes the missile after launch
    - Directs missile along a prescribed path until midcourse or terminal guidance begins
  - Specific techniques of these guidance phases will be explored fully in a future lecture
- Guidance is required for all intelligent projectiles
  - Guidance can be computed in the weapon (inertial guidance)
    - Weapon relies target track data to form commands
      - Communications with the firing platform
      - RF and IR sensors in the weapon provide target information
  - Guidance can be computed on the firing platform (command guidance)
    - Requires communications with the firing platform
    - Almost always requires a transition to terminal guidance

Midcourse vs Terminal Guidance
Weapon Guidance & Control

- Midcourse guidance (MCG) has many advantages, specifically for longer range engagements
  - Reduces the amount of time an illuminator is required for a semi-active missile
    - Increases depth of fire
    - Increases firepower
  - Can provide guidance commands long before the weapon sensor can detect the target
  - Use of complex guidance laws designed for specific purposes
    - Maximize kinetic energy at intercept
    - Influence the approach angle of the weapon at handover and/or intercept
- Terminal guidance (TG) traditionally is designed for one purpose – hit the target
  - Can be designed to select an aimpoint on the target
    - Provided from WCS as an offset from leading edge of the target
    - Based upon some measureable feature (heat signature, length)
  - Uses sensors on the weapon to update target states and form guidance commands
    - Close proximity of the sensor to the target means smaller track errors and more accurate commands than MCG

The MCG Functional Flow
Weapon Guidance & Control

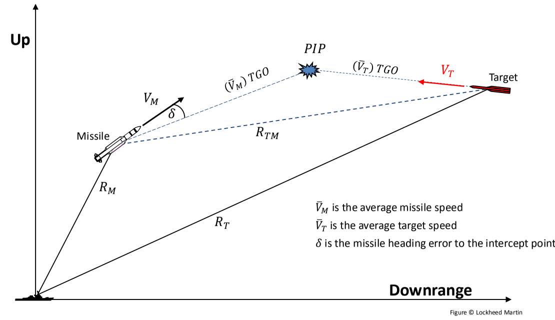
- Input: Missile states
  Target states
- Output:Acceleration command, N_C
- Intercept point computation requires
  - An estimate of time-to-go, TGO
  - Target trajectory strategy (assumed)
- Common assumed target trajectories
  - Straight and level
  - Turn to some key point with maneuver assumption
  - Artificial location
- MCG can be command (CMCG) or inertial (IMCG)



$R_{IP}, TGO,$ and T_{INT} are Used throughout WCS Processing for Engagement Monitoring and Resource Scheduling

Intercept Point Computation
MCG Functional Flow

- The key to modern midcourse guidance is intercept point prediction
  - The intercept point is computed using the intercept triangle



Intercept Triangle
Intercept Point Prediction

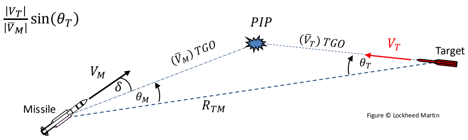
- The simplest implementation of an intercept point computation assumes the target trajectory is straight and level

  $$\bar{V}_T \equiv V_T$$

- The assumption of a non-constant average weapon speed will be considered later. For now, we will use the exiting nomenclature $\bar{V}_M$ to indicate the average remaining weapon speed at this instance
- The intercept triangle angles are defined as follows:

  $$\cos(\theta_T) = -\hat{V}_T \cdot \hat{R}_{TM}$$

  $$\sin(\theta_M) = \frac{|V_T|}{|V_M|}\sin(\theta_T)$$



Solving for the Intercept Point
Intercept Point Prediction

- Using basic geometry, we define TGO

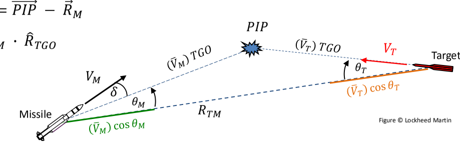
  $$TGO = \frac{|R_{TM}|}{\cos(\theta_M)\,|\bar{V}_M| + \cos(\theta_T)\,|V_T|}$$

- Which allows us to determine the PIP and the heading error

  $$\overrightarrow{PIP} = \vec{R}_T + (\vec{V}_T)\,TGO$$

  $$\vec{R}_{TGO} = \overrightarrow{PIP} - \vec{R}_M$$

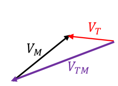
  $$\delta = \hat{V}_M \cdot \hat{R}_{TGO}$$



Time To Go Approximation
Intercept Point Prediction

- For simple systems, or engagements where the weapon speed is nearly constant as a function of time, an approximation of TGO can be computed using the missile to target closing speed, V_C

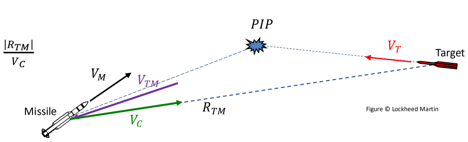
  $$\vec{V}_{TM} = \vec{V}_T - \vec{V}_M$$



  Note that $V_C = -\dot{R}_{TM}$

  $$V_C = -\vec{V}_{TM} \cdot \hat{R}_{TM}$$

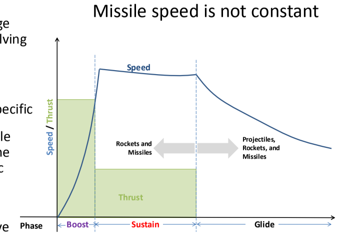
  $$TGO = \frac{|R_{TM}|}{V_C}$$



Average Missile Velocity
Intercept Point Prediction

- To this point, we assumed an accurate estimate of the average missile speed over the remaining flight was available
- Finding a means to compute the average remaining missile speed is crucial to solving the intercept triangle
  - This is one of the most important concepts in MCG
  - Estimating this value is weapon specific
- Methods of estimating remaining missile speed require detailed knowledge of the guidance law and weapon aerodynamic properties
- Without this knowledge, a high fidelity weapon simulation as part of a recursive algorithm is required within WCS to find the PIP and TGO

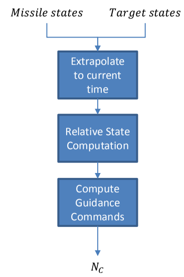
Missile speed is not constant



The TG Functional Flow
Weapon Guidance & Control

- Input: Missile states from weapon IMU
  Target states from weapon sensor system
- Output:Acceleration command, N_C
- Both missile and target states are estimated by functions internal to the weapon
  - Terminal guidance is a type of inertial guidance
  - There is no "command terminal guidance"
- There is no computation of intercept point
- Higher order target states (acceleration, jerk, etc.) may be used to augment the guidance commands
- Short timeline allows for the assumption of constant missile speed

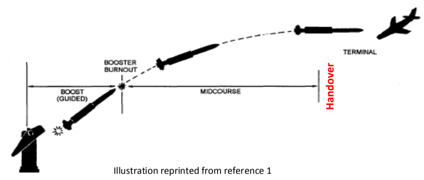
$$TGO = \frac{|R_{TM}|}{V_C}$$



The ONLY Goal of Terminal Guidance is to Generate Commands that Result in the Weapon Colliding with the Target

Handover Support

- Ensure the weapon is provided with the information and resources needed to complete the engagement
  - Target cueing information
  - Additional resources / information required for terminal guidance (illuminators, etc.)



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Handover is the Handshake Between the Midcourse and Terminal Phases of Flight

When is Handover Support Required?
Handover Support

- Handover support is only considered if the weapon can alter its trajectory during flight
- One of two additional conditions must be true for handover support to be required
  - Significant changes in target cueing information since last provided to the weapon
    - Requires uplink to provide more accurate information
    - More robust systems may provide handover support throughout the engagement
  - The weapon's seeker is semi-active
    - Requires an illuminator
- Handover support is typically executed at predetermined time-to-go ($T_H = TGO$)
  - It represents the earliest time at which the illuminator is needed to support the engagement
    - For home all the way (HAW) systems, $T_H = TOF$ (time of flight of the missile)
    - For MCG systems, $T_H \ll TOF$ under most circumstances
  - Reducing the duration of the support lightens the load on system resources

Illumination
Handover Support

- The ability of the illuminator to support the engagement is tied directly to the following:
  - Scheduling of the illuminator for support when needed
  - Providing enough reflected energy at the missile seeker ($power\ density > threshold$)
    - Bi-static radar range equation

$$PDMS = \frac{P_T\ G_T\ \sigma_{RCS}}{L_{IL}\ (4\pi)^2\ R_T^2\ R_{TM}^2}$$

- Where:
  - $PDMS$ Power density at the missile seeker
  - P_T transmit power of the illuminator
  - G_T gain of the antenna
  - σ_{RCS} radar cross section of the target
  - L_{IL} transmit losses of the illuminator
  - R_T distance from the RF source to the target
  - R_{TM} distance from the target to the missile seeker

Radar Range Equation
Handover Support

- The radar range equation can be decomposed into the segments of the RF path

$$PDMS = \frac{P_T\,G_T}{4\pi\,L_{IL}}\,\frac{\sigma_{RCS}}{R_T^2}\,\frac{1}{4\pi\,R_{TM}^2}$$

- Where:
  - $\frac{P_T\,G_T}{4\pi\,L_{IL}}$ Transmit power in the direction in which the gain applies
  - $\frac{P_T\,G_T}{4\pi\,L_{IL}} \times \frac{\sigma_{RCS}}{R_T^2}$ Power reflected from target of size σ_{RCS} at range R_T
  - $\frac{P_T\,G_T}{4\pi\,L_{IL}} \times \frac{\sigma_{RCS}}{R_T^2} \times \frac{1}{4\pi\,R_{TM}^2}$ Power per unit area at the receiver located R_{TM} from the target
- If receive gain is known, the radar range equation can be extended to consider the receiver

$$PDMS = \frac{P_T\,G_T}{4\pi\,L_{IL}} \times \frac{\sigma_{RCS}}{R_T^2} \times \frac{1}{4\pi\,R_{TM}^2} \times \frac{G_R\,\lambda^2}{4\,\pi}$$

  - G_R is the gain of the receiver
  - λ is the wavelength of the RF energy

Illumination
Handover Support

- Illuminator beam width determines how much power is lost due to poor pointing (G_T)
- Often times, it is convenient to lump the illuminator characteristics into a single term

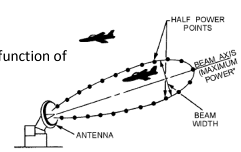
$$ILL_C = \frac{P_T\,G_{T_0}}{(4\pi)^2\,L_{IL}}$$

G_{T_0} is the maximum antenna gain (no pointing error)

$$PDMS = (ILL_C)\left(\frac{1}{G_{T_{err}}}\right)\left(\frac{\sigma_{RCS}}{R_T^2\,R_{TM}^2}\right)$$

$P_{G_{err}}$ is the gain lost due to pointing error

- The ability of the illuminator to properly support is a function of
  - Pointing accuracy
  - Target range from the illuminator at time, T_H
  - Missile to target range at time, T_H



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Communications
Handover Support

- All non-ballistic weapons require inflight updates if
  - Significant changes in the target cue has occurred since the last update
    - Target has deviated from the expected flight path
    - Target cue uncertainty has grown
- Some systems require near continuous communications to the weapon
  - Command to intercept systems
    - Weapon has no seeker
    - Weapon can maneuver
- Some systems conserve radar resources by only sending communications the weapon when an update is perceived to be required
  - Robust systems may provide handover support throughout the engagement
  - Tightly integrated systems may require continuous communications for auxiliary engagement information

Auxiliary Handover Support
Inflight Processing

- At times additional information can be provided to the weapon at handover
  - Preferred sensor frequencies
    - Sensor deconfliction among other weapons in the combat system
    - Avoidance of "unavailable" frequencies
  - Environmental information
  - Electronic Attack information
  - Modifications in communication protocol
- Environmental information that affects sensor and TDD operations
  - Multipath
  - Low altitude intercept
  - Overland /over water engagement

The More Information Provided to the Weapon, the More Need for Communications on Periodic Basis Rather than a One Time Event

Weapon Tracking
Inflight Processing

- The need to track the weapon is dependent upon many things
  - Intelligent projectile vs simple projectile
  - Integration level of the combat system
  - Communications
  - Guidance technique
  - Engagement monitoring/evaluation
- There are many reasons why a weapon will not be tracked
  - Simple projectiles are "fire and forget"
  - Intercept range is within any tracking system capability
  - Automated rounds produce too many individual projectiles to track
- Some weapons and tracked by happenstance rather than planned

As a General Rule, the More Robust Combat Systems Rely Upon Weapon Tracking to Increase Awareness and Improve Engagement Evaluation

Methods of Weapon Tracking
Weapon Tracking

Radar tracks weapon independent of communications

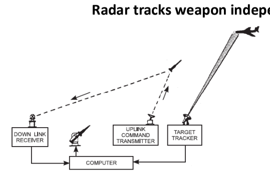


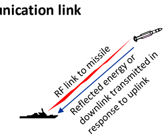
Illustration reprinted from reference 1

- Radar tracks missile as needed
- Separate radar is responsible for communications with the missile
- Typically used when tracking radar is a different frequently than the communications radar

Radar tracks weapon with communication link

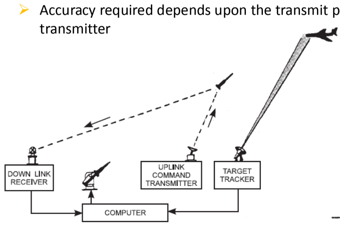
- Radar sends RF message to missile
- Energy reflected off the missile is captured by the platform's radar

  or
- Missile sends downlink in response to uplink (beacon track)



Communications
Weapon Tracking

- Combat systems which communicate with the weapon must have knowledge of the weapon location in order to communicate
- The same fundamental limitations on tracking an objects exits when communicating with a weapon
  - RF signal must be aimed at the weapon accurately
  - Accuracy required depends upon the transmit power and the antenna shape of the RF transmitter



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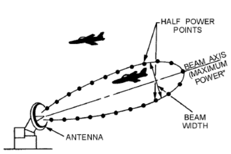

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Weapon Tracking & Guidance
Weapon Tracking

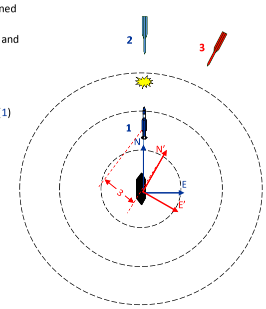
- All guidance methods require weapon state information in addition to state information of the engaged threat
  - Terminal guidance provides both weapon and target states to the guidance system
  - All other forms of guidance rely upon target states from a sensor not located on the weapon
- Mitigation of coordinate system alignment errors and gyro drift is necessary for long range intercepts
  - A single sensor tracking both weapon and target drastically reduces the bias between missile and target in the guidance loop
  - Use of a single sensor to track both missile and target is often called differential tracking
- Alignment to an agreed upon coordinate system can remove internal weapon errors by comparing weapon position data to another sensor source (preferably the source that is tracking the target)
  - Gyro drift
  - Alignment errors during initialization

An Example of Alignment Bias

- Let's focus on a missile being launched from a rail launching system
  - The missile is provided its orientation relative to East North UP (ENU) on the rail via an initialization message from the launcher
- The orientation of the missile provided to during the missile initialization message contains error
  - Small alignment error is common when aligning to physical entities
    - Mechanical alignment accuracy due to machine limitations
    - Measurement accuracy limitations
    - The tolerance on the alignment error is often specified during construction and is typically small
  - To note the difference between the true ENU and the "missile ENU", the missile ENU system will be noted as the ENU' system

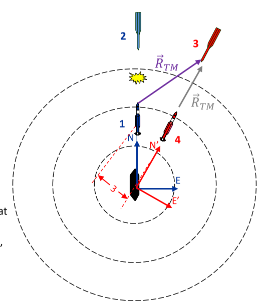
Realization of Alignment Bias

- To the right is an illustration that contains a single engagement as defined in different coordinate frames
  - Frame A (blue): True East, North, Up as defined by the launcher and the radar
  - Frame B (red): East, North, Up according to the missile
- Missile is launched due north to intercept a threat
  - At a certain time after launch, the missile is located at position (1)
  - {E: 0 miles, N: 8 miles}.
- At the same time, the missile is provided cueing information that indicating the target is located at position (2).
  - {E: 0 miles, N: 16 miles}
- In true (blue) frame A:
  - Target is located at position (2) {E: 0, N: 16}
  - It is directly in front of the true missile (1)) {E: 0, N: 8}
- In misaligned (red) missile frame B:
  - Target is located at position (3) {E': 0, N': 16}
  - To the missile, the missile has a significant component of its position in the – E' direction {E': -3, N': 7.5}



Compensating for Alignment Bias

- When the missile attempts to search for the target, it performs some basic math:
  - Find the search line to the target: $\vec{R}_{TM} = \vec{R}_T - \vec{R}_M$
  - Missile ($\vec{R}_M$) is located at: {E': -3, N': 7.5}
  - Target ($\vec{R}_T$) is located at: {E': 0, N': 16}
  - $\vec{R}_{TM}$ is: {E': 3, N': 8.5}
- Missile forms the vector at which the target search is to be centered:
  - Search line, $\vec{R}_{TM}$: {E': 3, N': 8.5} from current missile position is expressed in purple on the illustration
  - Target is actually at position (2). No target is found at position (3)
- A simple means of accounting for the bias is as follows:
  - Provide the missile with it's own position, according to the combat system radar: {E: 0, N: 8}
  - Missile views this as a correction to its own position: {E': 0, N': 8}, and now the missile, in the ENU' system, is at position (4)
- Now the missile is able to find the target, denoted by the gray line
  - Missile ($\vec{R}_M$) is located at: {E': 0, N': 8}
  - Target ($\vec{R}_T$) is located at: {E': 0, N': 16}
  - $\vec{R}_{TM}$ is: {E': 0, N': 8}



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Post Intercept Processing
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- Kill Assessment

Support Functionality
- Track Processing (filtering)
- Resource Management
- Scheduling
- Displays

Post Intercept Processing

- Used to determine the outcome of the engagement and use inventory judiciously
- Kill assessment
  - A means to determine if the target has been neutralized
  - Many different methods tests are used to glean information
- Engagement evaluation
  - Considers the results of kill assessment and operator interaction to determine the outcome of the engagement (success, fail, unknown)
  - Assists in the decision to re-engage or to consider the engagement complete
  - If engagement is complete, WCS performs "clean up" to prepare for the next engagement or ready to re-engage

Simpler Systems Use Optics (Visuals) to Perform Kill Assessment and Engagement Evaluation

Kill Assessment

Post Intercept Processing

- Most of the methods of kill assessment involve analyzing data just prior to intercept and comparing it to data after intercept
  - Looking for modest to severe changes in the data set
  - An accurate estimate of the intercept time is crucial (accurate TGO is required)
- Method used to determine if the target is neutralized is dependent upon information available
  - Sensor measurements on target and weapon data can be used to analyze track changes
  - Missile communications may provide additional information
  - Passive sensors can search for RF energy being emitted from the target
  - Visual inspection
- Kill assessment must be timely
  - The decision to relaunch decision must be made swiftly in a self-defense situation

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References

1. NAVEDTRA 14110, *Gunner's Mate 1 & C*. November 1996
2. NAVEDTRA 14190, *Navy Electronics& Training Series*. September 1998
3. *Midcourse Guidance*, Corse, J., Lockheed Martin Midcourse Guidance Course. 1998