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The Application of Parameter Dependency Diagrams in System Design: A missile design example

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OUTLINE

- Introduction
- System Architectural Design Process
- Introducing Parameter Dependency Diagrams into System Design
- A Missile Design Example
- Conclusions

INTRODUCTION

- This paper introduces the concept of parameter dependency diagrams to the system design process.
- Design Parameters are defined as the aspects of the physical and functional characteristics of systems and their elements that are an input to its design process.
- A system design as referred to in this paper can be described as a subset of the design parameter space provided by the physical architecture elements and connections.

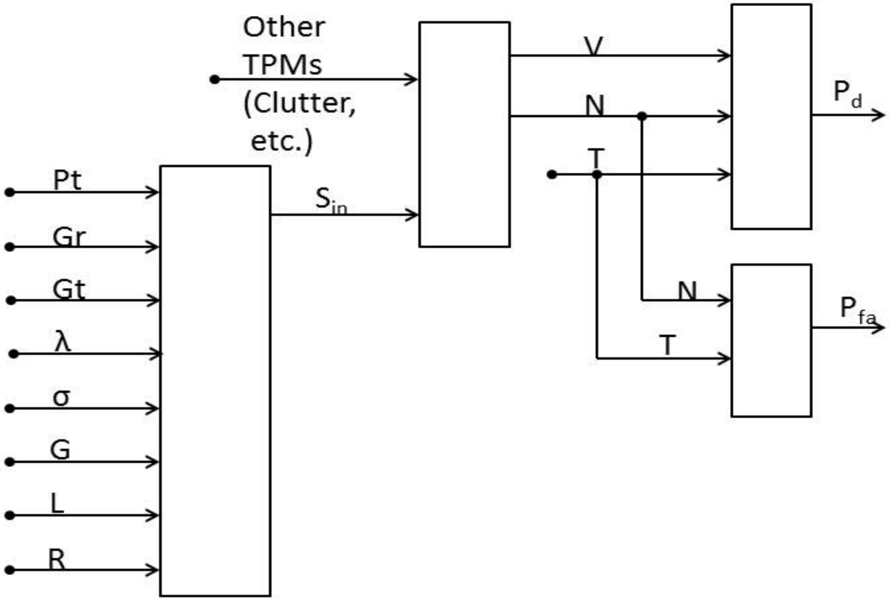
INTRODUCTION

- The architectural design process (in ISO15288) entails both the design of the system architecture (logical and physical elements and interconnections), and the definition of the elements, usually done in the form of parameters.
- Parameter dependency diagrams were developed by Eisner:
  - One begins to identify the Key Performance Parameters (KPP's) of the system under consideration
  - These are prioritized in terms of design impact (design driver)
  - For each parameter the question is raised: what does this parameter depend on?
  - This question is repeated for each of the dependent parameters until the dependencies are simple quantitative relationships

INTRODUCTION

Parameter Dependency Diagram (PDD) radar example:

- KPP is probability of detection P_d and probability of false alarm P_{fa}
- This depends on signal V and noise N
- These depend on:
    - Power transmitted, Pt
    - Gain of receiving antenna, Gr
    - Gain of transmitting antenna, Gt
    - Wavelength, λ
    - Target radar cross section, σ
    - Receiver processing power gain, G
    - Receiver power losses, L
    - Range to target, R



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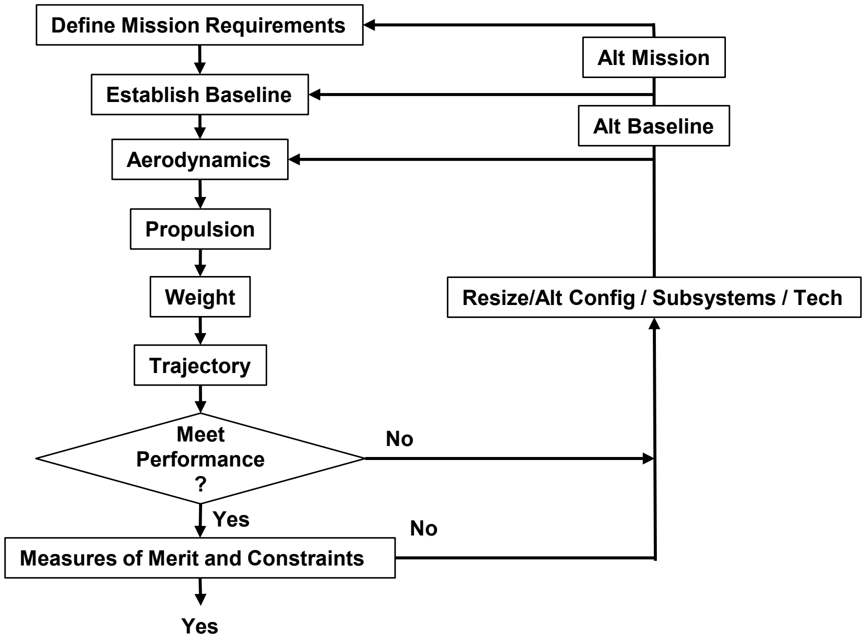
ARCHITECTURE DESIGN PROCESS

- Traditional Architectural Design processes are iterative by nature. See Fleeman on missile design:



ARCHITECTURE DESIGN PROCESS

- The traditional approach is that of Fleeman; one can start anywhere and just keep iterating the process until it converges to a solution.
- The above process is iterative and it is not very dependent on exactly where you start. This is one of the big problems with designing a system with highly interrelated elements.
- The purpose of this paper is to develop a more optimal system design process that reduces the number and scope of iterations required.
- This paper looks at bringing the parameter dimension into the system design process itself.

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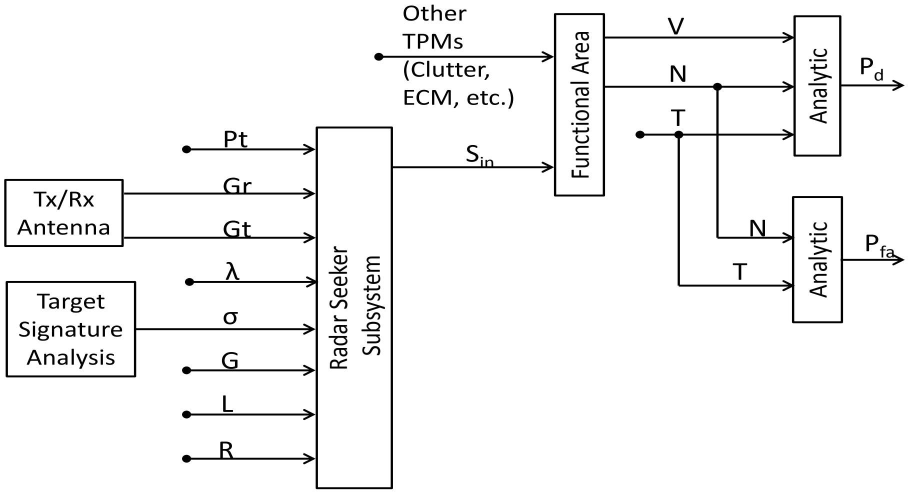
PDD's IN SYSTEM DESIGN

- This paper proposes that the blocks in Eisner's PDD's are also important to system design as they denote not just analytical relationships (formulae) but also functional relationships (that may be so complex as to encompass functional areas), and also physical system elements.
- The parameter inputs to a physical element block are design parameters that are used to design these blocks.
- The PDD can be used to define the functional areas as well as the physical elements of the system in a logical top-down process

PDD’s IN SYSTEM DESIGN

Using Eisner’s example we can now look at the blocks:

- The Pd and Pfa have an analytic relationship with voltage (V), noise (N) and threshold (T)
- The relationship between incoming signal (Sin) in and voltage and noise is a complex function of the environment and is determined through a functional area model
- The signal is a function of the radar seeker subsystem that is governed by the radar equation
- The Tx/Rx antenna gain is a subsystem
- Target signature is analysis and measurement



ARCHITECTURE DESIGN PROCESS

To summarize the proposed system design process:

- Define the KPPs by ranking performance requirements based on their impact on the system's purpose and the value system of the client.
- Draw up the PDD as defined by Eisner.
- Define analytical, functional areas and physical element relationships in the PDD.
- Use the functional areas in the PDD to draw up the highest level logical representation of the system, e.g. an EFFBD. Do functional analysis to the level where they can be allocated to physical elements.
- Allocate the functions to the physical elements defined in the PDD.
- Determine the physical interfaces (mechanical, electrical and logical) between the system elements. Allocate the physical elements to the overall system's structure/shape/form.
- Do detail design of each of the physical elements of the system.

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EXAMPLE

The example is a surface-to-air missile that has to be delivered to a system of systems integrator. The missile system has to provide:

- Protection over an area of 2.5km x 2.5km
- A probability of kill of >80% against:
  - A Mirage 2000 fighter aircraft
  - And a Mk82 500lb bomb (including GPS guided bombs)
- At least 4 missiles - simultaneously attacking four widely spaced targets.
- A flight time (T_{of}) of <8s to a maximum slant range (R_{max}) of 6km over a half hemisphere
- 24/7 protection for a 3 month deployment under all the weather conditions in which the targets can fly.

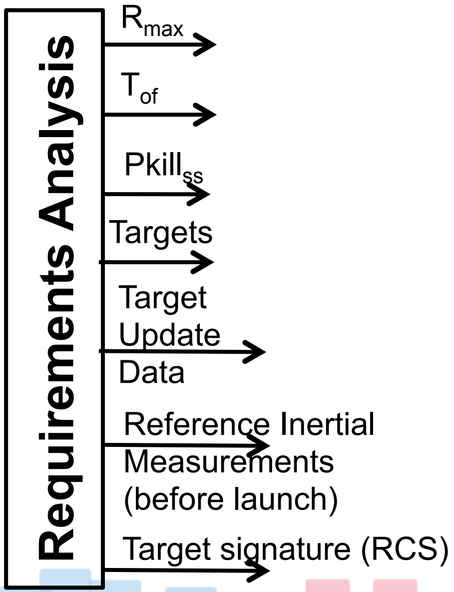
EXAMPLE

REQUIREMENTS ANALYSIS:

- A Pkill of 80% implies a mission reliability of 0.89 and a single shot Pkill ($Pkill_{ss}$) of a functioning missile of 0.89.
- The four simultaneous missiles requirement imply:
  - A fire and forget missile with its own terminal guidance seeker
    - The all-weather requirements implies a radar seeker
    - The seeker shall be lock-on after launch with a short lock-on range
    - The target signature data has to be provided for lock-on-after-launch
  - A data uplink to update allocated target position to the missile in flight
  - An inertial mid-course guidance with reference inertial data to calibrate the on-board navigation system before launch
  - A vertical launcher that can launch in four direction near simultaneously

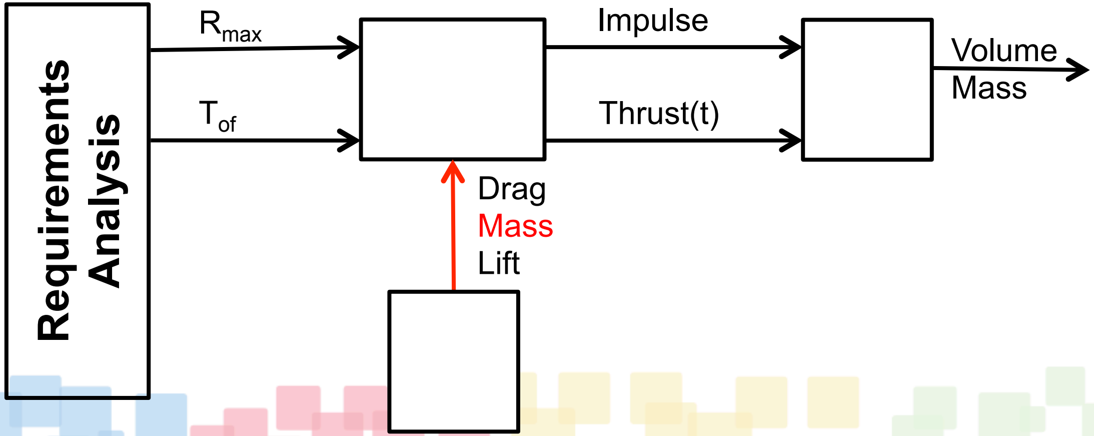
EXAMPLE

- The highest priority KPP's and TPM's are from the URS; R_{max}, T_{of}, Targets, and from the derived requirements we have; $Pkill_{ss}$, Target Update Data, Reference inertial data and Target signature (RCS):



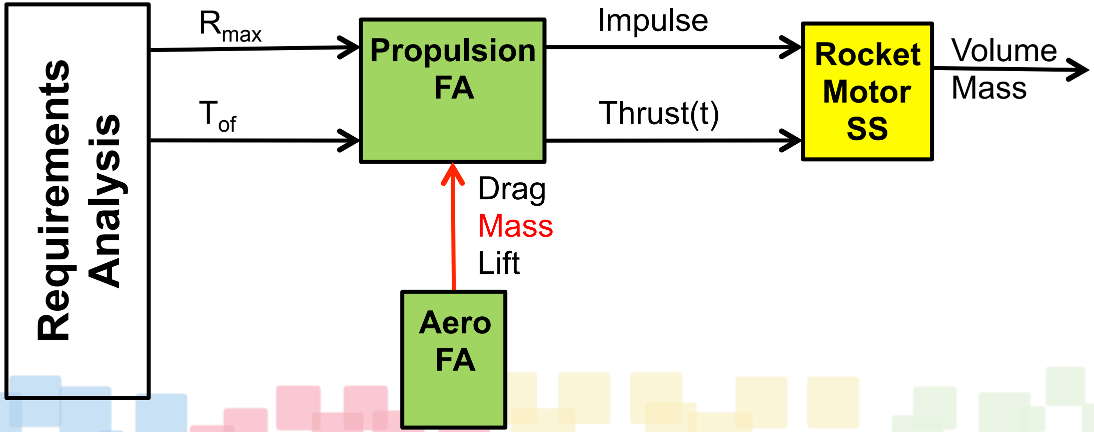
EXAMPLE

- The range and time of flight parameters are dependent on impulse, thrust profile, drag and mass.
- Impulse and thrust depends on available volume and mass .
- Drag, mass and lift is determined by the aerodynamic design



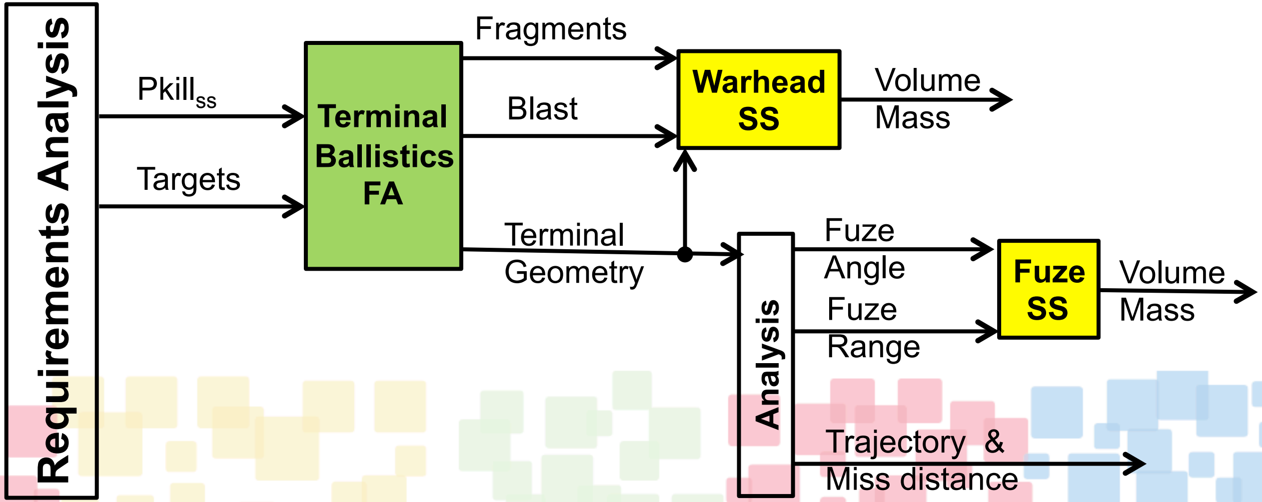
EXAMPLE

- The relationship between impulse, thrust profile, drag, mass and lift is complex and is determined by the Propulsion functional area.
- Impulse and thrust is provided by a rocket motor subsystem.
- Drag, mass and lift is determined by the aerodynamic functional area



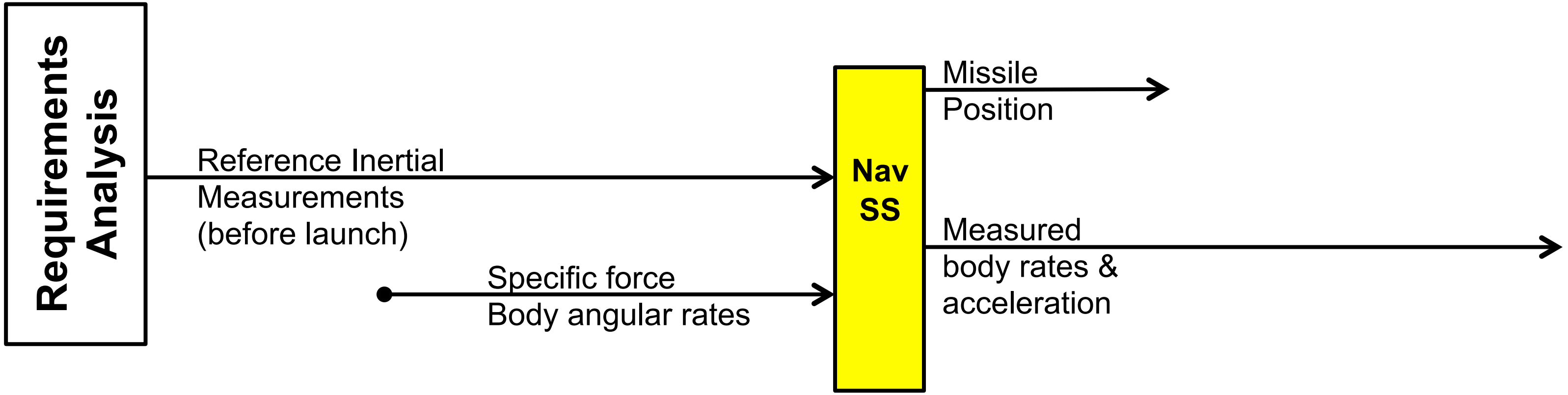
EXAMPLE

- The $Pkill_{ss}$ and the Targets are the design parameters for the terminal ballistics functional area. It provides the fragment pattern, blast radius and terminal geometry requirements.
- These three requirements are the design parameters for the warhead subsystem, the output of which are volume and mass parameters.
- The terminal geometry provides the design parameters for the fuze subsystem and the terminal trajectory and miss distance.



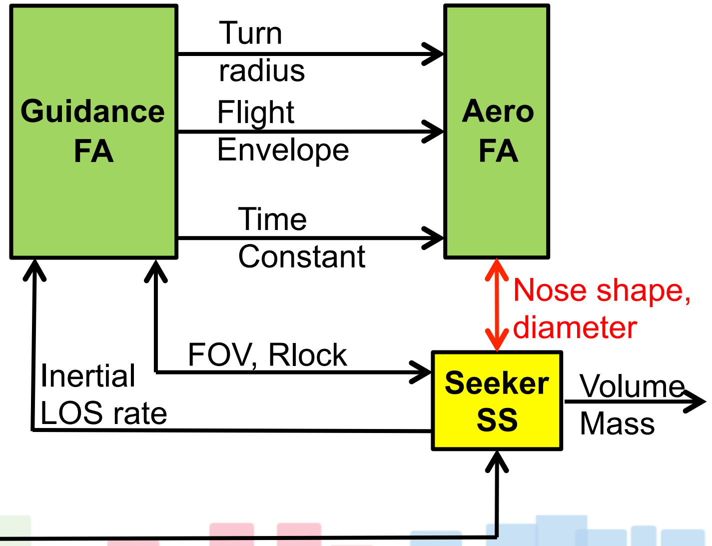
EXAMPLE

- The reference inertial measurements are design inputs for the on-board navigation subsystem. It also uses measurements of specific force and body angular rates to determine missile position, measured body angular rates and accelerations:



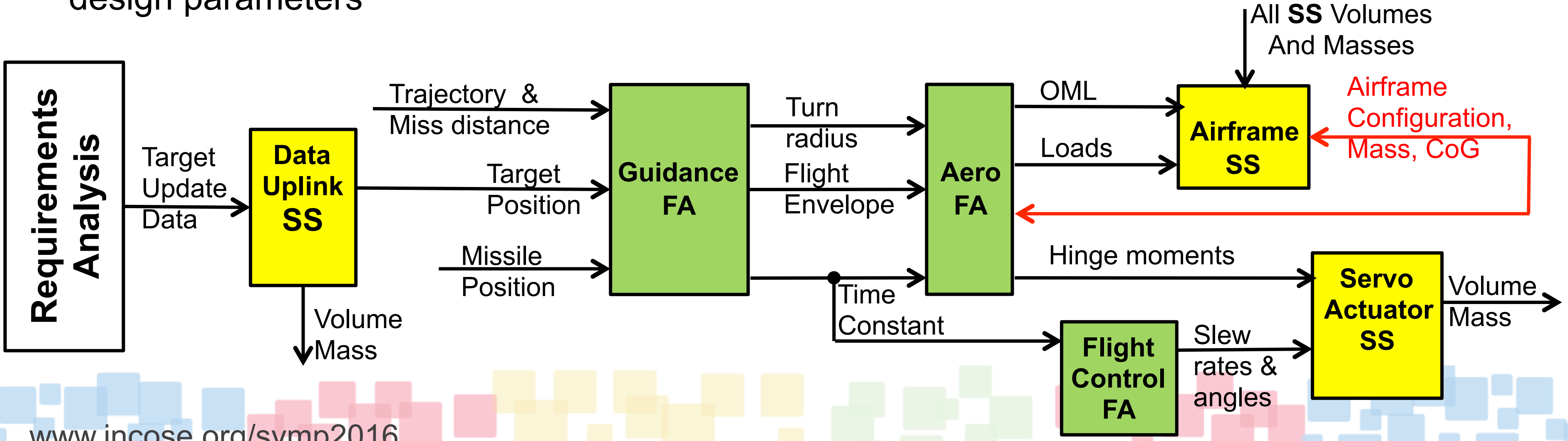
EXAMPLE

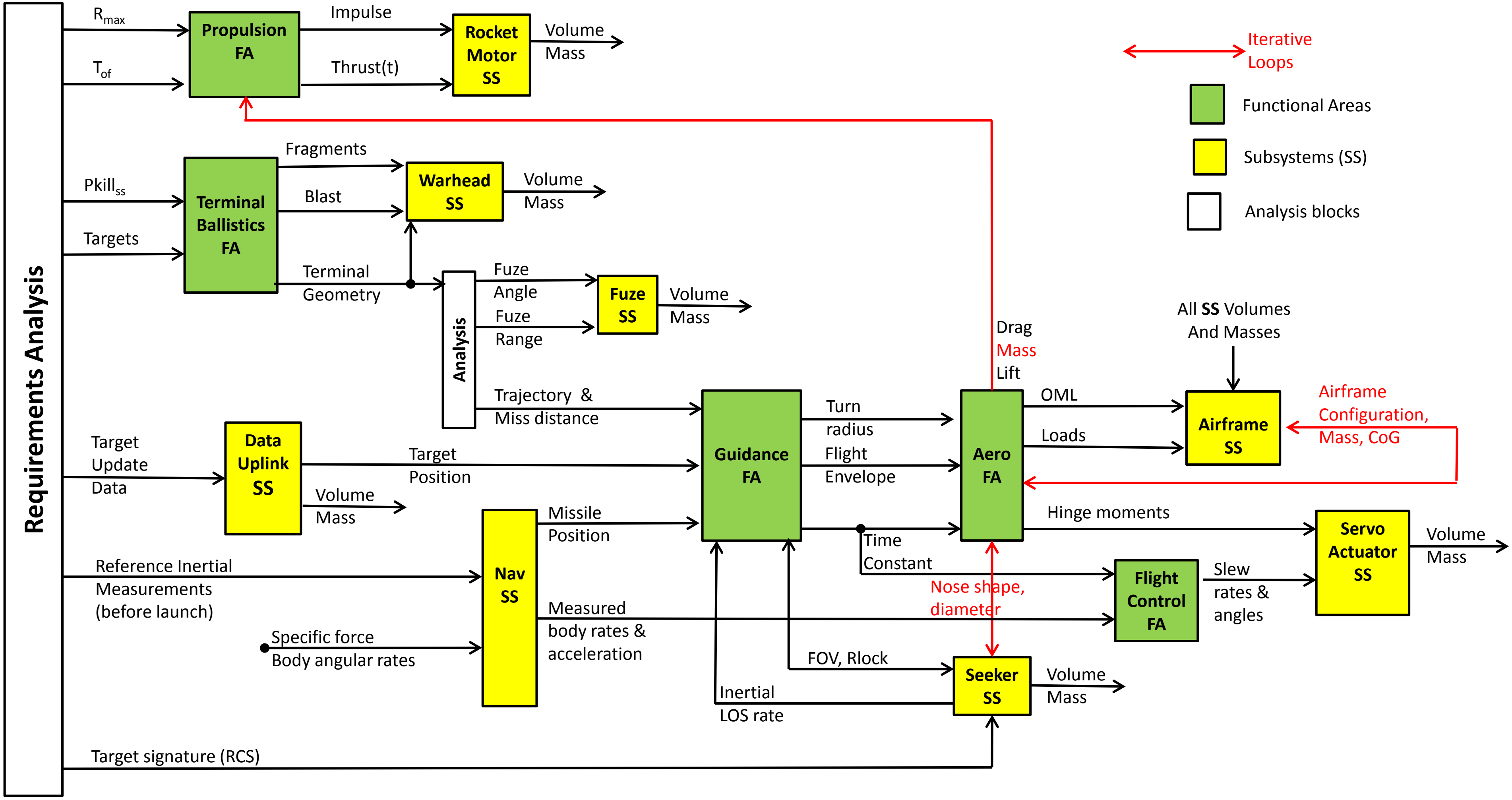
- The radar seeker subsystem design parameters are:
  - From guidance: Field of view and lock on range
  - From Requirements the target signature parameters (radar cross section)
  - From aero an input on the nose diameter and nose shape
- It provides guidance with inertial line of sight rates and the aero with nose shape and diameter inputs:



EXAMPLE

- The measured target position, the terminal trajectory and the missile's own position are design parameters for the guidance functional area.
- Guidance determines the airframe turn radius, flight envelope and time constant that are design parameters for aero and flight control functional areas
- Aero determines the outer mould line and loads for the airframe subsystem
- The servo actuator requires hinge moments and control surface slew rate and angles as design parameters

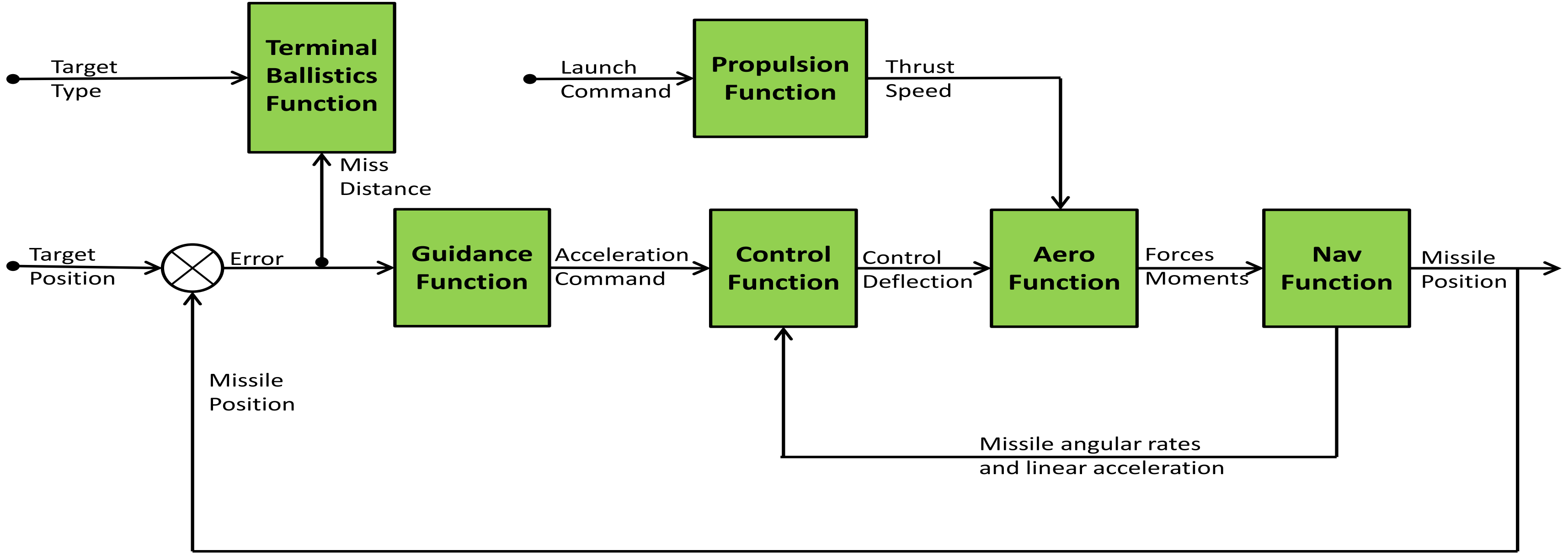




Requirements Analysis
R max
T of
Propulsion FA
Impulse
Thrust(t)
Rocket Motor SS
Volume
Mass
Iterative Loops
Functional Areas
Subsystems (SS)
Analysis blocks
Pkill ss
Targets
Terminal Ballistics FA
Fragments
Blast
Warhead SS
Volume
Mass
Terminal Geometry
Analysis
Fuze Angle
Fuze Range
Fuze SS
Volume
Mass
Drag
Mass
Lift
All SS Volumes And Masses
Trajectory &
Miss distance
Guidance FA
Turn radius
Flight Envelope
Aero FA
OML
Loads
Airframe SS
Airframe Configuration, Mass, CoG
Target Update Data
Data Uplink SS
Target Position
Volume
Mass
Missile Position
Nav SS
Hinge moments
Servo Actuator SS
Volume
Mass
Time Constant
Flight Control FA
Slew rates & angles
Reference Inertial Measurements (before launch)
Nose shape, diameter
Measured body rates & acceleration
Specific force
Body angular rates
FOV, Rlock
Seeker SS
Volume
Mass
Inertial LOS rate
Target signature (RCS)

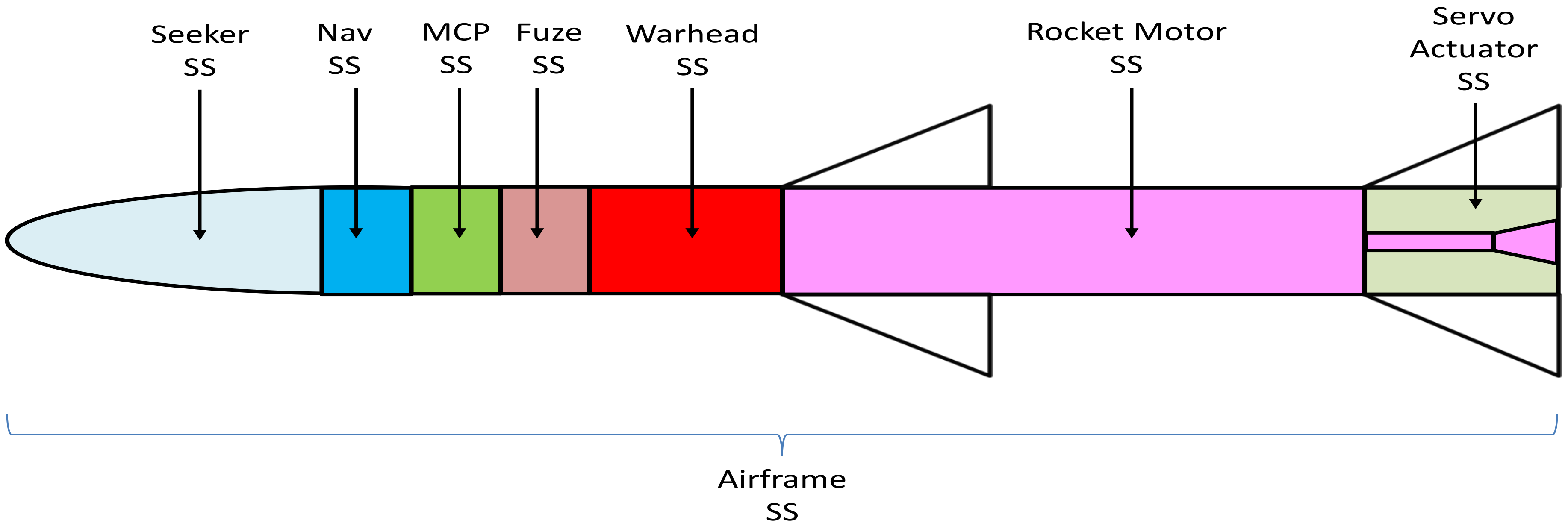
Logical Representation

- The PDD's functional area blocks can now be used to develop the high level functional flow block diagram:



Physical Representation

- The PDD's physical blocks can now be used to develop a physical architecture. E.g. the mechanical view:



CONCLUSIONS

- The PDD assists in the definition of functional and physical elements in the system.
- The PDD provides a method to model the key performance parameters in terms of the actual design, aiding in the evaluation of various architectural design options.
- PDD's gives a logical sequence in the design of complex systems that minimize the number and scope of iterations
- The PDD provides a logical construct to assist requirements traceability
- It is recommended to experiment with PDD's as a system design tool in other domains to generalize the use of this technique.