Requirements Specification:

- A structured document that sets out the services the system is expected to provide.
- Should be precise so that it can act as a contract between the system procurer and software developer. Needs to be understandable by both.
- Describes what the system will do but not how it will do it (objectives but not how objectives will be achieved.

Design Specification:

- An abstract description of the software that serves as a basis for (or describes) detailed design and implementation
- Describes how the requirements will be achieved.
- Primary readers will be software designers and implementers rather than users or management.
- Goals and constraints specified in requirements document should be traceable to the design specification (and from there to the code.

Contents of Requirements Documents

Introduction: Describes the need for the system and places it in context, briefly describing its functions and presenting a rationale for the software. Describes how the system fits into the overall business or strategic objectives of the organization commissioning the software.

System Model: Shows the relationships between the system components and the system and its environment. An abstract data model should also be described if appropriate to the type of system.

System Evolution: Fundamental assumptions on which the system is based and anticipated changes due to hardware evolution, changing user needs, etc.

Functional Requirements: The services provided for the user. This includes timing and accuracy requirements.

Contents of Requirements Documents (2)

Constraints: Constraints on how the goals can be achieved (restrictions on behavior of software and freedom of designer), e.g., safety, hardware, programming languages, standards that must be followed. Includes quality requirements such as maintainability, availability, etc.

Priorities: Guides tradeoffs and design decisions if all requirements and constraints cannot be completely achieved.

Interfaces to the Environment: Input or output interfaces and relevant assumptions about environmental components with which the software will be interacting.

Glossary: Definitions of technical terms used in the document.

Indexes: Various types of indexes may be provided.

Attributes of a good requirements document:

- Readable and understandable by customers, users, and designers.
- Specifies only external system behavior (black box)
- Structured to be easy to change.
- Specifies both goals and constraints.
- Able to serves as a reference for system maintainers.
- Consistent, complete, unambiguous, realistic, and testable
- Specified acceptable responses to undesired events.
- Specifies what should not do as well as what should do.
- Specified incremental subsets if desried or minimum and maximum functionality
- Specifies changes anticipated in the future (for both environment and software)

Requirements must be testable

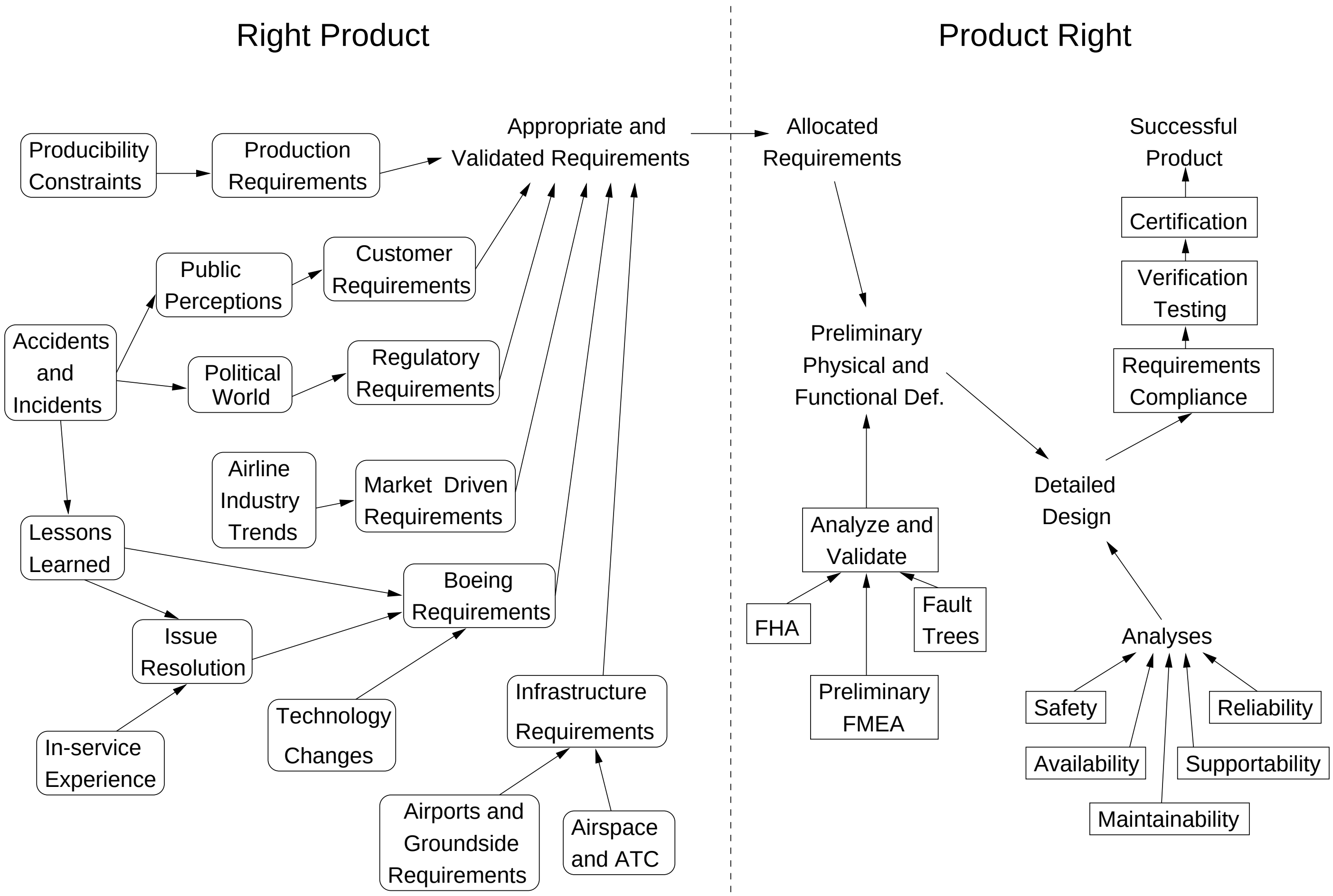
An untestable requirement:

The system shall be easy to use by experienced controllers and shall be organized in such a way that user errors are minimized.

A testable requirement:

Experienced controllers shall be able to use all the system functions after a total of two hours training. After this training, the average number of errors made by experienced users shall not exceed two per day.

Ensuring a Successful Product

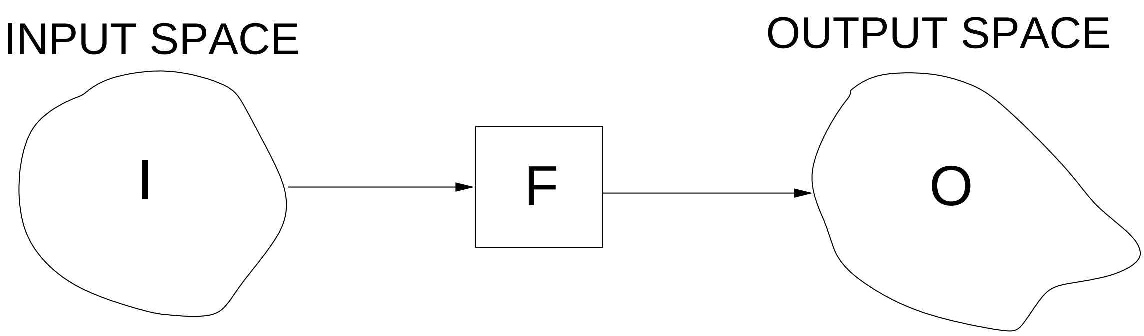


Types of Specifications

- Informal
  - Free form, natural language
  - Ambiguity and lack of organization can lead to incompleteness, inconsistency, and misunderstandings
- Formatted
  - Standardized syntax (e.g., UML)
  - Basic consistency and completeness checks
  - Imprecise semantics implies other sources of error may still be present.

Types of Specifications (2)

- Formal
  - Syntax and semantics rigorously defined.
  - Precise form, perhaps mathematical.
  - Eliminate imprecision and ambiguity.
  - Provide basis for mathematically verifying equivalence between specification and implementation.
  - May be hard to read without training.
  - Semantic distance too great?



F(I) = O

- A program is a mathematical object
- A programming language is a mathematical language.
- Therefore, we can prove properties about the program.

  e.g. does it do what it is supposed to do
  does it not do anything harmful

- Building a model like engineers do, but need discrete rather than continuous mathematics.

Input−Output Assertions

S {P} Q

If S holds before execution of S, then Q holds afterward.

Examples:

1. sum = 0 { for i=1 to n do sum:=sum+a(i) } sum = $\sum_{j=1}^{n} a_j$

2. **proc** search(A,n,x) **int;**

   pre $n \geqslant 0$

   post (result = 0 $\wedge$ $\forall$ i $\in$ {1,...,n} : A[i] $\neq$ x) $\vee$
   (result = i $\wedge$ $1 \leqslant i \leqslant n$ $\wedge$ A[i] = x $\wedge$
   $\forall$ i $\in$ {1,...,i−1} : A[i] $\neq$ x)

Abstract Model Specifications

- Build an abstract model of required software behavior using mathematically defined (perhaps using axioms) types (e.g., sets, relations).

- Define operations by showing effects of that operation on the model.

- Specification includes:
  - Model
  - Invariant properties of model
  - For each operation:

    name
    parameters
    return values
  - Pre and post conditions on the operations

Z (pronounced Zed)

- Z specifications are made up of "schemas"

- A schema is a named, relatively short piece of specification with two parts:

  - Above the line: the definition of the data entities
  - Below the line: the definition of invariants that hold on those data entities

Z : Defining the Abstract Model

```
┌─ Library ─────────────────────────
│ books:  P  BOOK
│ status:  BOOK  ↦  STATUS
├───────────────────────────────────
│ books =  dom  status
└───────────────────────────────────
```

- Declaration says library has two visible parts of its state:
  - books is a set of BOOKS, which are atomic elements.
  - status is a partial function that maps a BOOK into a STATUS (which is another atomic element that can take values In or Out)
- The invariant says the set of books is precisely the same as the domain of the function status.
  - Says every book in the Library has exactly one status
  - Two books may have the same status.

Example of a legal state for Library is:

books = {Principia Mathematica, Safeware}

status = (Principia Mathematica $\mapsto$ In,
Safeware $\mapsto$ Out}

Z : Defining Operations

```
┌─ Borrow ──────────────────────────
│ Δ Library
│ book?: BOOK
├───────────────────────────────────
│ status (book?) = In
│ status' = status ⊕ (book? ↦ Out)
└───────────────────────────────────
```

- Δ Library declaration says operation modifies state of Library
- book? is the input
- A prime indicates the value after the operation
- The first invariant defines a pre−condition on the operation, i.e., the book to be borrowed must be currently checked in.
- The second invariant defines the semantics of borrowing, i.e., it overwrites the entry in the status function for the borrowed book.

Z : Proving Properties

Example: After a borrow operation, the set of books in the library remains unchanged.

books' = books

$books' = dom\ status'$ [from invariant of Library]

$= dom\ (status \oplus \{book? \mapsto Out\})$ [from post−condition of Borrow]

$= dom\ (status \cup \{book? \mapsto Out\})$

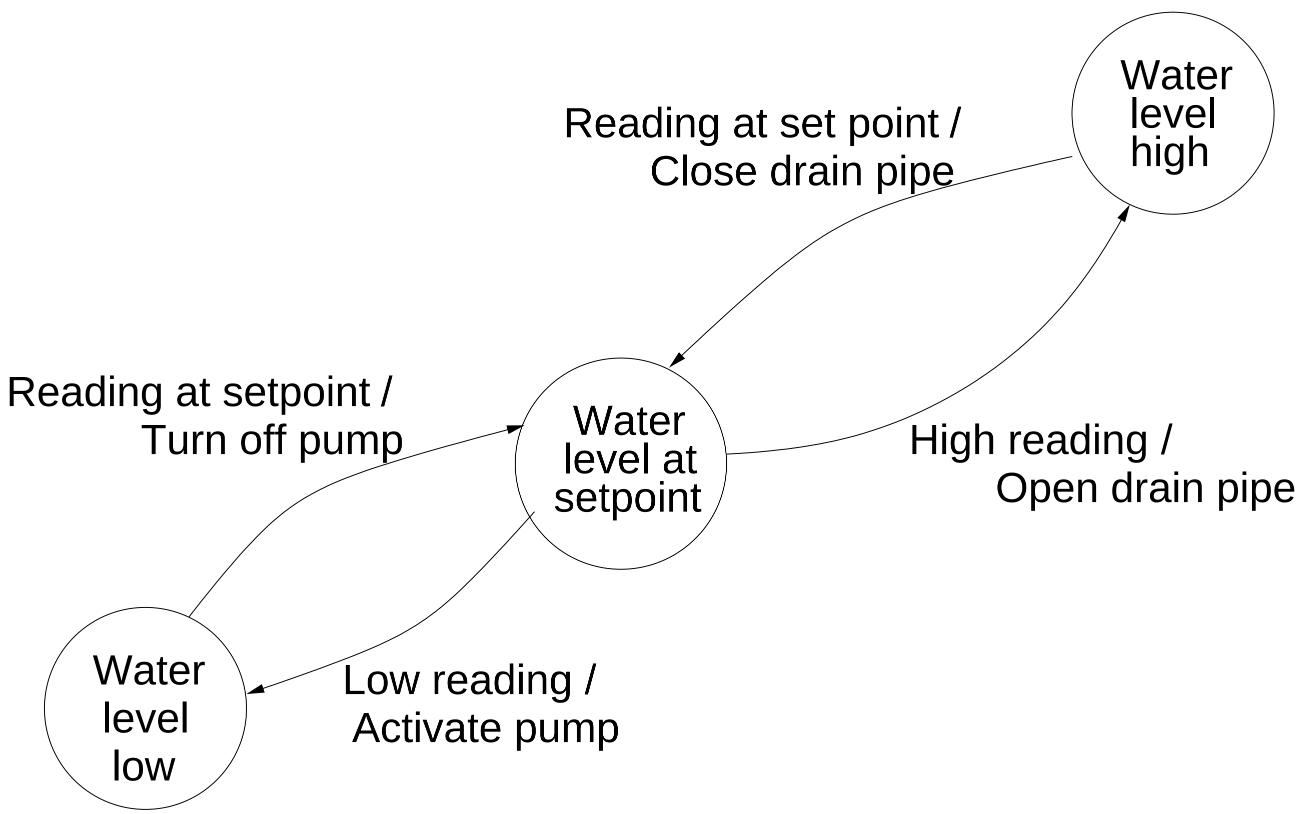
$= dom\ status \cup dom\ (\{book? \mapsto Out\})$

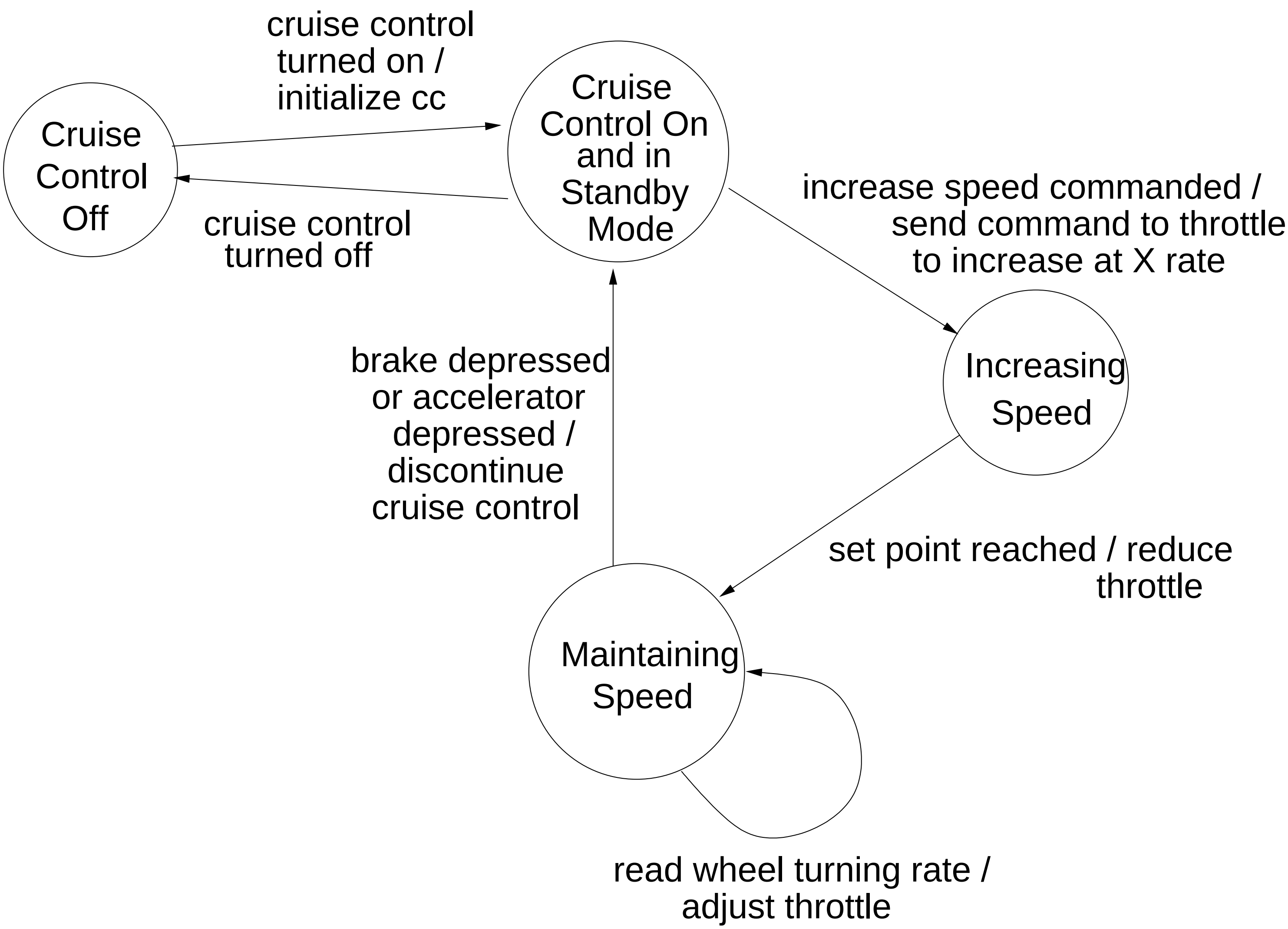
$= book \cup book?$

Follow from mathematics

$= book$ [true because first invariant of Borrow implies that book? is an element of books]

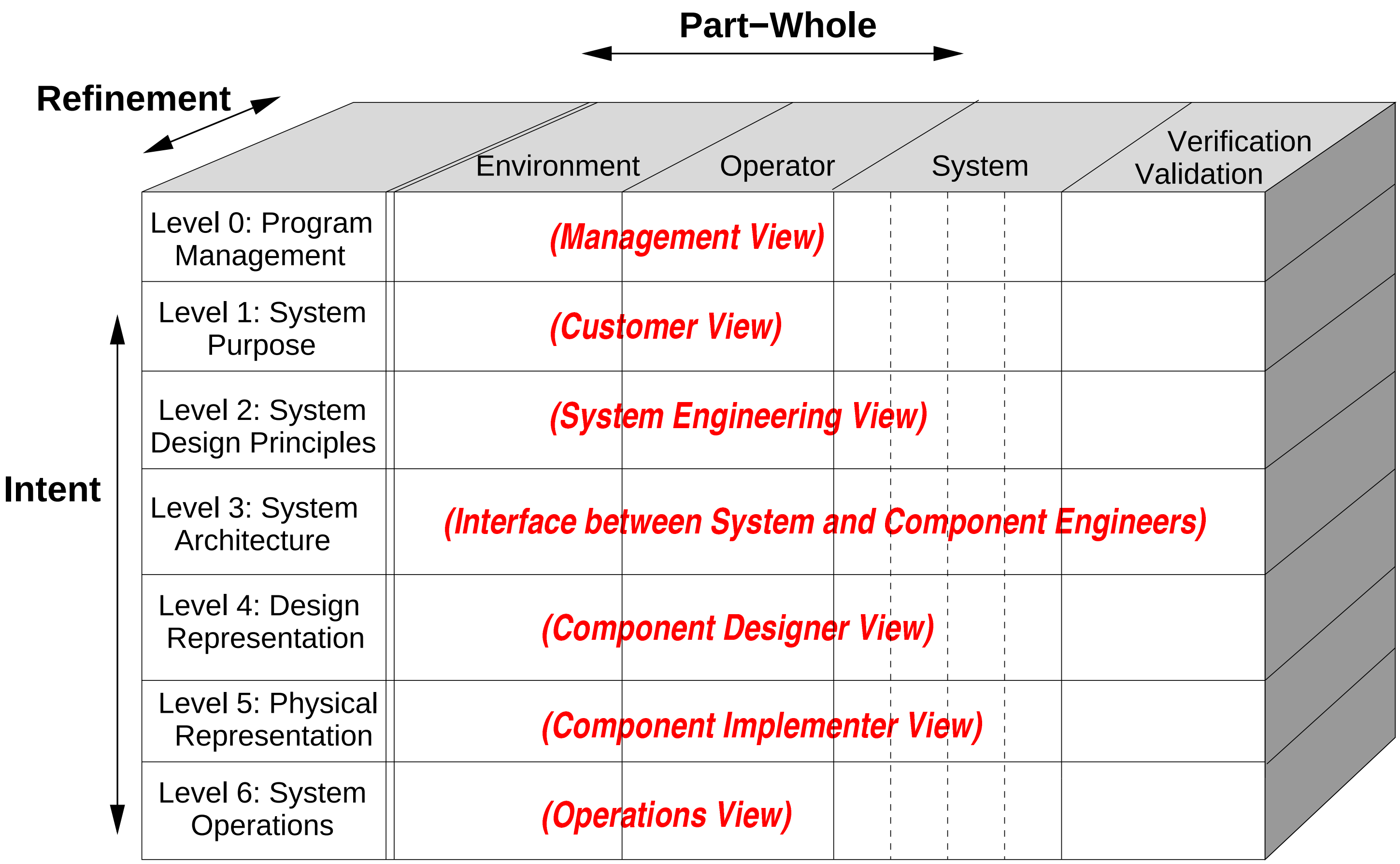
Example of a State Machine Model




cruise control
turned on /
initialize cc
Cruise
Control
Off
Cruise
Control On
and in
Standby
Mode
cruise control
turned off
increase speed commanded /
send command to throttle
to increase at X rate
Increasing
Speed
brake depressed
or accelerator
depressed /
discontinue
cruise control
set point reached / reduce
throttle
Maintaining
Speed
read wheel turning rate /
adjust throttle

SpecTRM

- System engineering tools for software−intensive systems
  - A "CATIA" for the logical parts of the system
  - Requirements errors found early while cheaper to fix
  - Goal of enhancing communication and expert review
- Integrates hazard analysis into engineering decision−making environment
  - Information available when needed and in form that has maximum impact on decisions.
- Documentation of design rationale
- Complete traceability
  - For verification and validation
  - To support change and upgrade process
- Based on
  - Cognitive engineering research on how experts solve problems
  - Basic principles of system engineering


Part−Whole
Refinement
Intent
Environment
Operator
System
Verification
Validation
Level 0: Program Management
Level 1: System Purpose
Level 2: System Design Principles
Level 3: System Architecture
Level 4: Design Representation
Level 5: Physical Representation
Level 6: System Operations
(Management View)
(Customer View)
(System Engineering View)
(Interface between System and Component Engineers)
(Component Designer View)
(Component Implementer View)
(Operations View)

	Environment	Operator	System and components	V&V
Level 0 Prog. Mgmt.	Project management plans, status information, safety plan, etc.			
Level 1 System Purpose	Assumptions Constraints	Responsibilities Requirements I/F requirements	System goals, high−level requirements, design constraints, limitations	Preliminary Hazard Analysis, Reviews
Level 2 System Principles	External interfaces	Task analyses Task allocation Controls, displays	Logic principles, control laws, functional decomposition and allocation	Validation plan and results, System Hazard Analysis
Level 3 System Architecture	Environment models	Operator Task models HCI models	Blackbox functional models Interface specifications	Analysis plans and results, Subsystem Hazard Analysis
Level 4 Design Rep.		HCI design	Software and hardware design specs	Test plans and results
Level 5 Physical Rep.		GUI design, physical controls design	Software code, hardware assembly instructions	Test plans and results
Level 6 Operations	Audit procedures	Operator manuals Maintenance Training materials	Error reports, change requests, etc.	Performance monitoring and audits

Level 1: Environment

- Description of environment in which interacts
- Assumptions about environment

EA−1: Altitude information is available from intruders with minimum precision of 100 feet

EA−2: All aircraft will have legal identification numbers

Level 1: Operator

- Pilot Responsibilities and Tasks
- Operator requirements

OP−5: TCAS advisories shall be executed in such a way as to minimize the aircraft's deviation from it's ATC clearance

Human−Machine Interface Requirements

HMI−3: A red visual alert shall be provided in the primary field of view for each pilot for resolution advisories.

Level 1 Functional Goals:

G1: Provide affordable and compatible collision avoidance system options for a broad spectrum of National Airspace users.

Level 1 Functional Requirements

FR−1: TCAS shall provide collision avoidance protection for any two aircraft closing horizontally at any rate up to 1200 knots and vertically up to 10,000 feet per minute.

Assumption: Commercial aircraft can operate up to 600 knots and 5000 fpm during vertical climb or controlled descent and therefore the planes can close horizontally up to 1200 knots and vertically up to 10,000 pfm.

TCAS does not display a resolution advisory.

- TCAS unit is not providing RAs.
  - <Self−monitor shuts down TCAS unit>
  - Sensitivity level set such that no RAs are displayed.
  - . . .
- No RA inputs are provided to the display.
  - No RA is generated by the logic
    - Inputs do not satisfy RA criteria
      - Surveillance puts threat outside corrective RA position.
        - Surveillance does not pass adequate track to the logic
          - <Threat is non−Mode C aircraft> → L.5
          - <Surveillance failure> → 1.23.1
        - <Surveillance error causes incorrect range or range rate to be calculated>
      - Altitude reports put threat outside corrective RA position
        - Altitude errors put threat on ground
          - <Uneven terrain> ↓ 2.19
          - <Intruder altitude error>
          - <Own Mode C altitude error> → 1.23.1
          - <Own radar altimeter error> → 1.23.1
        - Altitude errors put threat in non−threat position.
        - . . .
      - <Intruder maneuver causes logic to delay RA beyond CPA> → SC4.2 ↓ 2.35
    - . . .
  - <Process/display connectors fail>
- <Display is preempted by other functions> → SC4.8 ↓ 2.22
- <Display hardware fails> → 1.23.1

TCAS displays a resolution advisory that the pilot does not follow.

- Pilot does not execute RA at all.
  - Crew does not perceive RA alarm.
    - <Inadequate alarm design> → 1.4 to 1.14 ↓ 2.74, 2.76
    - <Crew is preoccupied>
  - <Crew does not believe RA is correct.> → OP.1
  - ...
- Pilot executes the RA but inadequately
  - <Pilot stops before RA is removed> → OP.10
  - <Pilot continues beyond point RA is removed> → OP.4
  - <Pilot delays execution beyond time allowed> → OP.10

Level 1: System Limitations

L−5: TCAS provides no protection against aircraft with non−operational or non−Mode C transponders [FTA−370]

Level−1 Safety Constraints and Requirements

SC−5: The system must not disrupt the pilot and ATC operations during critical phases of flight nor disrupt aircraft operation. [H3]

SC−5.1: The pilot of a TCAS−equipped aircraft must have the option to switch to the Traffic−Advisory mode where traffic advisories are displayed but display of resolution advisories is prohibited [2.37]

Assumption: This feature will be used only during final approach to parallel runways when two aircraft are projected to come close to each other and TCAS would call for an evasive maneuver [6.17]

SC−7: TCAS must not create near misses (result in a hazardous level of vertical separation that would not have occurred had the aircraft not carried TCAS) [H1]

SC−7.1: Crossing maneuvers must be avoided if possible. [2.36, 2.38, 2.48, 2.49.2]

SC−7.2: The reversal of a displayed advisory must be extremely rare [2.51, 2.56.3, 2.65.3, 2.66]

SC−7.3: TCAS must not reverse an advisory if the pilot will have insufficient time to respond to the RA before the closest point of approach (four seconds or less) or if own and intruder aircraft are separated by less then 200 feet vertically when ten seconds or less remain to closest point of approach [2.52]

Example Level−2 System Design for TCAS

SENSE REVERSALS ↓Reversal−Provides−More−Separationm−301

2.51 In most encounter situations, the resolution advisory sense will be maintained for the duration of an encounter with a threat aircraft.

[SC−7.2]

However, under certain circumstances, it may be necessary for that sense to be reversed. For example, a conflict between two TCAS−equipped aircraft will, with very high probability, result in selection of complementary advisory senses because of the coordination protocol between the two aircraft. However, if coordination communications between the two aircraft are disrupted at a critical time of sense selection, both aircraft may choose their advisories independently.

[FTA−1300]

This could possibly result in selection of incompatible senses.

[FTA−395]

2.51.1 [Information about how incompatibilities are handled]

Level 3 Specification (modeling) language goals

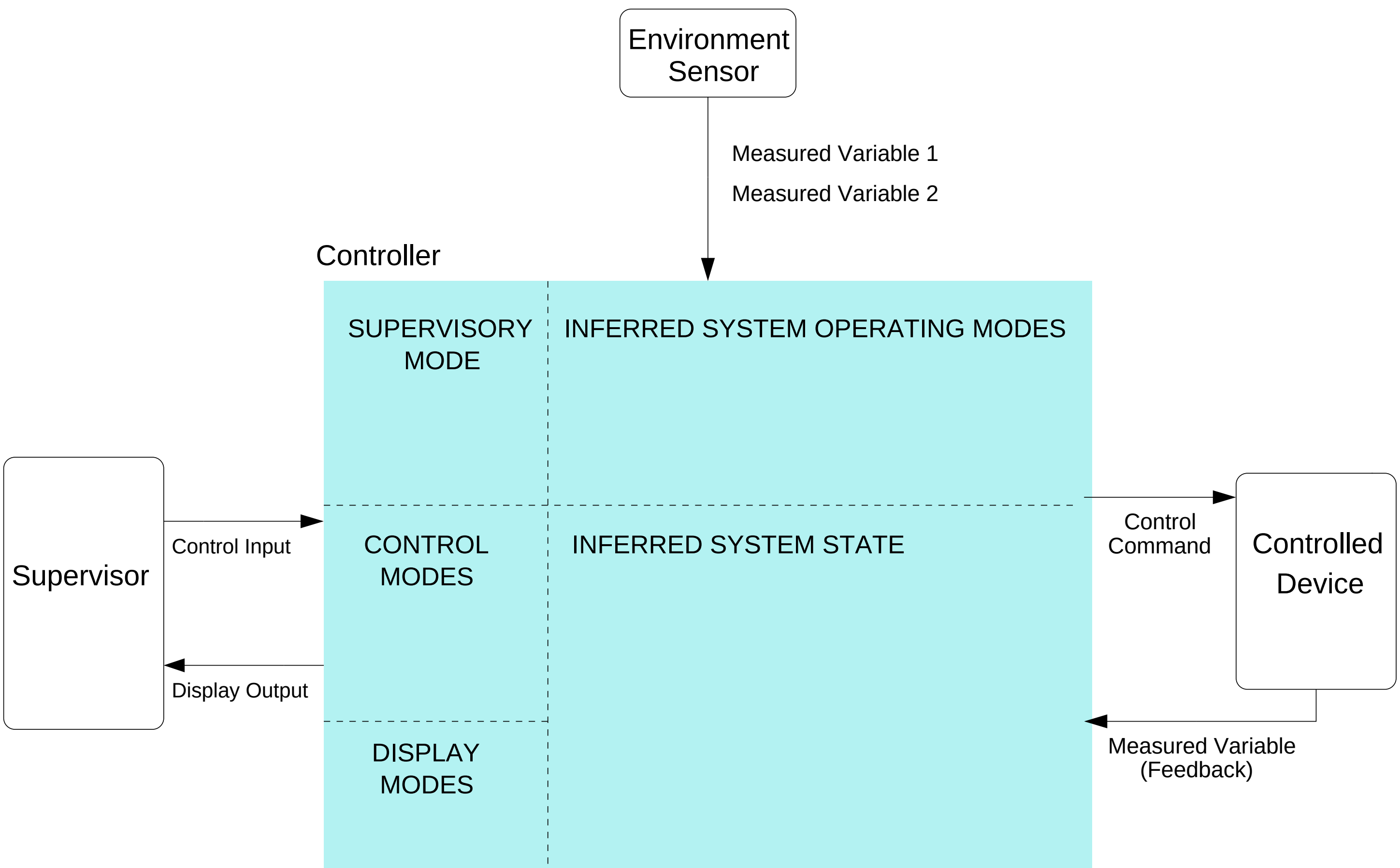
- Specify allocation of functionality to components
- Readable and reviewable
  - Minimize semantic distance
  - Minimal: blackbox behavior only (transfer function)
  - Easy to learn
  - Unambiguous and simple semantics
  - Visualization tools
- Complete (can specify everything need to specify

  Analyzable (formal, mathematical foundation)
  - Executable (acts as a prototype)
    Animation and simulation
  - Tools to check completeness, consistency, nondeterminism
  - Includes human (operator) procedures and analysis
- Extensible (e.g., connecting to MATLAB, Simulink)

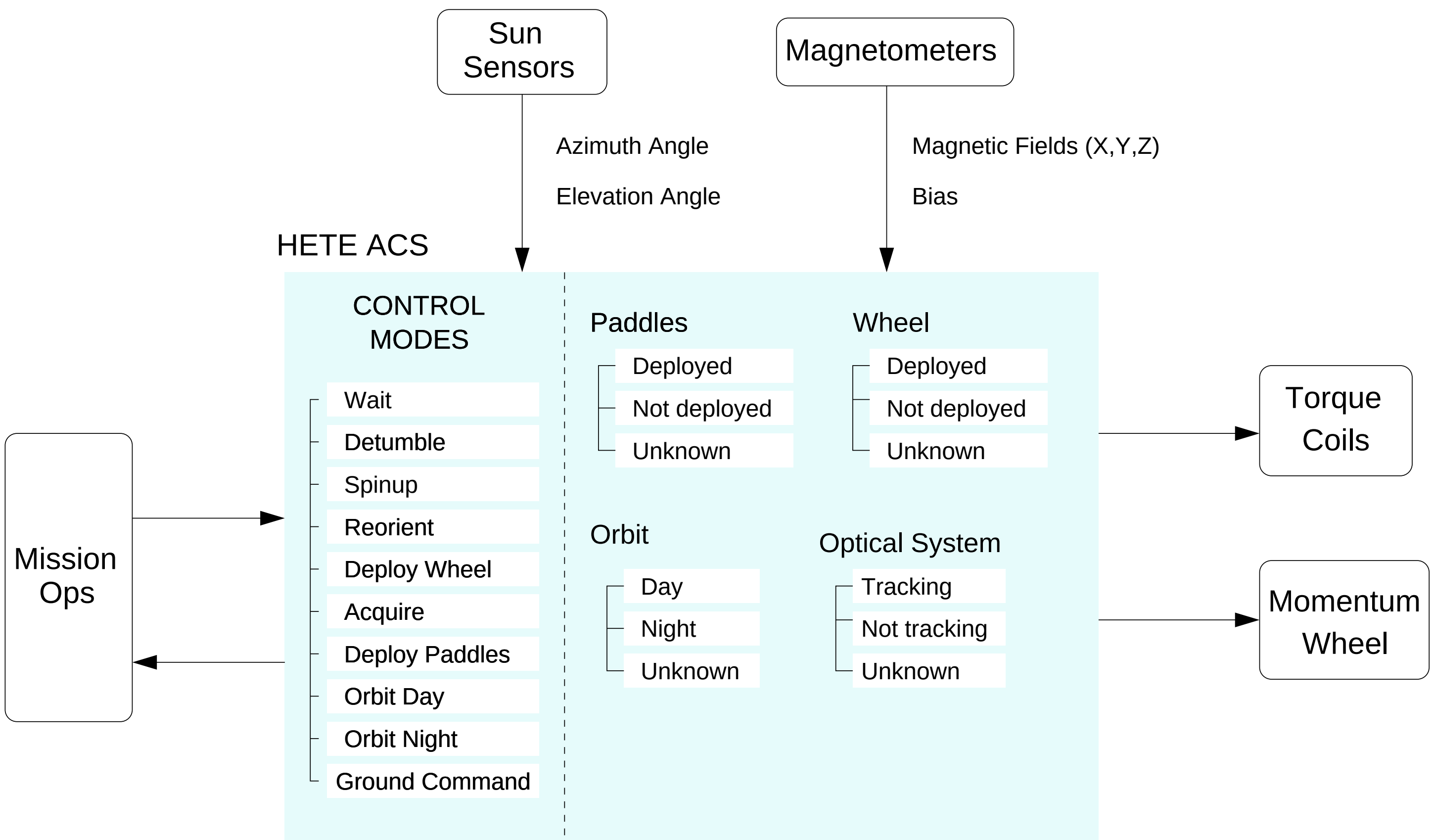
  API, built on Eclipse

SpecTRM−RL

- Combined requirements specification and modeling language
- A state machine with a domain−specific notation on top of it.
  - Includes a task modeling language
  - Can add other notations and visualizations of state machine
- Enforces or includes most of completeness criteria
- Supports specifying systems in terms of modes
  - Control modes
  - Operational modes
  - Supervisory modes
  - Display modes


Environment Sensor
Measured Variable 1
Measured Variable 2
Controller
SUPERVISORY MODE
INFERRED SYSTEM OPERATING MODES
Supervisor
Control Input
Display Output
CONTROL MODES
INFERRED SYSTEM STATE
Control Command
Controlled Device
DISPLAY MODES
Measured Variable (Feedback)

SpecTRM Model of HETE Attitude Control System



ACS Mode (2)

= Detumble (Mode 1)

The purpose of detumble mode is to minimize the magnitude of body momuntum vector in the X−Z plane. As soon as the magnitude falls below a threshold,e software should transition to spinup mode. The mode delay provides hysteresis in the mode transitions to prevent the software from jumping between modes too rapidly.

In detumble mode, the wheel actuator shall be controlled such that the wheel maintains the velocity it had upon entering the mode, and the magnetic moment along the Y axis shall be controlled to minimize the angular velocity about the X and Z axes.

		OR					
Control Mode	Wait	T					
	Detumble		T	T			
	Spinup				T	T	
	Ground Control						T
State Values	Time since entered wait >= 10 sec	T					
	Time since entered detumble < 100 sec		T	F			
	xz momentum error > xz momentum error threshold			T	T	T	
	Time since entered spinup >= 100 sec				T	T	
	Paddles in−state deployed				F		
	Optical system in−state tracking					F	
	Time since entered ground control >= 10 sec						T

Output Command

Name

Destination:
Acceptable Values:
- **Units:**
- **Granularity:**
- **Exception Handling:**
- **Hazardous Values:**

Timing Behavior:
- **Initiation Delay:**
- **Completion Deadline:**
- **Output Capacity Assumptions:**
  - **Load:**
  - **Min time between outputs:**
  - **Max time between outputs:**
- **Hazardous timing behavior:**
- **Exception−Handling:**

Feedback Information:
- **Variables:**
- **Values:**
- **Relationship:**
- **Min. time (latency):**
- **Max. time:**
- **Exception Handling:**

Reversed By:
Comments:
References: ↑ ↓

DEFINITION

= ...

Requirements Analysis

- Model Execution, Animation, and Visualization
- Completeness
- State Machine Hazard Analysis (backwards reachability)
- Human Task Analysis
- Test Coverage Analysis and Test Case Generation
- Automatic code generation

Does It Work?

- It is being used for aerospace and automotive systems.
  - Have found important errors in requirements
  - Very complex systems modeled
- Level 3 models used to maintain TCAS II for past 10 years
  - All suggested changes and upgrades first modeled and evaluated through simulation.

Summary

- Integrate design rationale and safety information into specification and its structure
- Capture domain knowledge (reusable architectures)
- Provides traceability from high−level requirements to detailed design and code.
- Blackbox models at Level 3
  - Executable and analyzable

    e.g., completeness, robustness, mode confusion, hazard analysis, test case generation, code generation
  - Specification acts as an executable prototype

    Can interface with system simulation
  - Visualization tools
  - Interface to contractors