Architecting Systems to Create Value

Ed Crawley
Ford Professor of Engineering, MIT
Founding President, Skoltech

With thanks to:
Dr. Bruce Cameron
Prof. Dov Dori
Many students!

2016 Sept 28
The Challenge

• We conceive, design, implement and operate complex and sometimes unprecedented systems

• Do they deliver sustained value?

• Are they architected well?
System + Architecture

System: A set of interrelated entities which perform a function, whose functionality is greater than the sum of the parts.

Architecture: The embodiment of concept, and the allocation of physical/informational function to elements of form, and definition of relationships among the elements and with the surrounding context.
Architecture is Form + Function
A Principle: complexity exceeds comprehension
The Power and Magic of Systems is in Emergence

Function

Performance

Reliability

Emergencies
Form and Function of the System

- How do we predict emergence?

<table>
<thead>
<tr>
<th>Function</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passengers</td>
<td>Transporting</td>
</tr>
<tr>
<td>Transport Aircraft</td>
<td>Instrument</td>
</tr>
<tr>
<td>Operand</td>
<td>Process</td>
</tr>
</tbody>
</table>

Operand ➔ Process ➔ System form
Entireties of the System: Form and Function

- Holism and focus
- Divide and conquer

<table>
<thead>
<tr>
<th>System Function</th>
<th>Entity Function</th>
<th>Entity Form</th>
<th>System Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move Passengers</td>
<td>Lift payload</td>
<td>Wing</td>
<td>Transport Aircraft</td>
</tr>
<tr>
<td></td>
<td>Propel vehicle</td>
<td>Air breathing engine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stabilize/ guide vehicle</td>
<td>Trailing edge surfaces</td>
<td></td>
</tr>
</tbody>
</table>
Relationships: Form and Function

- Interactions occur when operands are shared
- Emergence is in interaction
Relationships:
Form and Function

- A different concept brings different interaction
Desired Emergence?

- Emergence can be predicted *a priori* by:
  - Precedent
  - Experimentation
  - Modeling

- For other systems, only human reasoning can be relied on to predict emergence – functional modeling helps guide us
Comprehensive Analysis of System Architectures

- These all systems! Use system thinking
- Requirements and concepts are intellectual stepping stone
Exchange Model of Stakeholder Interaction

- **Value** is delivered in an exchange - *benefit at cost*
- **Successful exchange** with a stakeholder occurs when:
  - Your outputs or outcomes meet their needs (benefit to them)
  - Their outputs or outcomes meet your need (cost to them)
- **A Principle:** the basis of stakeholder engagement
Identify Stakeholders for Human Space Exploration

Executive & Congress

International partners

US People

Security

DoD, DHS
Intelligence
Other Gov. Ag. in security roles
(DoE)

Educator

Economic

K-12
Universities
Other (e.g. museums)

Commercial
Health providers
Other Gov. Ag. in non-security roles
(FAA, HHS, EPA, NOAA)

Media

Science

Organized media
Direct delivery media

Explorers
Scientists
NASA
(exploration related offices)

Scientists
Other Gov. Ag. in science roles (NIH)
NASA scientists
Model Needs of Each Stakeholder

- Identify the needs of stakeholders, and what flows to them to satisfy that need
- Assess the relative importance of the flow to the stakeholder
- Create a network model of the stakeholder community with the project as the central node
- Analyze to gain insight into the delivery of value in the network

Science

- Science knowledge
- Science technology
- Science community

- Space acquired data
- Skilled & motivated workforce
- NASA Science funding
- NASA Space technology
- Scientific data
- Plans and progress reports
- Media entertainment and information

- Stable and rewarding employment
- Science opinions and policy support
- Scientific knowledge
- Science systems
Modeling Value Flow in Stakeholder Network
Key Architectural Decisions

What are the key architectural features that separate these two designs?

What are the decisions?

Architectural? Sensitive? Connected?

Tube and Wing Family

BWB Family

Credit: Robert Liebeck / Boeing
Apollo Architecture – What are the Decision?

Source: http://www.hq.nasa.gov/alsj/a17/AS17-145-22261HR.jpg
Identifying the Decisions and Choices – Apollo

Mission parameters:
- Mission mode related (Earth launch, EOR, Moon arrival, LOR, Moon departure)
- Command Module Crew: 2 or 3?
- Lunar Module Crew: N/A, 1, 2 or 3?

Fuel/propulsion type related:
- Service module fuel: cryogenic or storable?
- Lunar module fuel: N/A, cryogenic or storable?

The three major categories of mission modes are captured: Direct, EOR, and LOR.

9 Decisions!
Representing the Decisions and Choices

<table>
<thead>
<tr>
<th>shortID</th>
<th>Decision</th>
<th>alt A</th>
<th>alt B</th>
<th>alt C</th>
<th>alt D</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOR</td>
<td>Earth Orbit Rendezvous</td>
<td>no</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>earthLaunch</td>
<td>Earth Launch Type</td>
<td>orbit</td>
<td></td>
<td>direct</td>
<td></td>
</tr>
<tr>
<td>LOR</td>
<td>Lunar Orbit Rendezvous</td>
<td>no</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>moonArrival</td>
<td>Arrival at Moon</td>
<td>orbit</td>
<td></td>
<td>direct</td>
<td></td>
</tr>
<tr>
<td>moonDeparture</td>
<td>Departure from Moon</td>
<td>orbit</td>
<td></td>
<td>direct</td>
<td></td>
</tr>
<tr>
<td>cmCrew</td>
<td>Command Module Crew</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lmCrew</td>
<td>Lunar Module Crew</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>smFuel</td>
<td>Service Module Fuel</td>
<td>cryogenic</td>
<td>storable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lmFuel</td>
<td>Lunar Module Fuel</td>
<td>NA</td>
<td>cryogenic</td>
<td>storable</td>
<td></td>
</tr>
</tbody>
</table>
Non-dominated Feasible Solutions

- **IMLEO vs. mission success probability**

**Points on the Pareto front:**

- Point 1: *von Braun-like*: Direct Mission, with 3 crew, storable propellants
- Point 2: Direct with 2 crew, storable propellants
- Points 3, 4, 5, 6: LOR missions.
- Point 3 is *Apollo-like*: LOR mission, storable propellants, 3 crew, 2 to surface
- Point 7: EOR mission, 2 crew with cryogenic propellants
- Point 8: *Soviet-like*: min mass configuration, LOR, 2 crew, 1 to surface.

**About 3 Good Architectures**
Decision Space View: helps us understand decision sequence

Degree of Connectivity

Degree of sensitivity

(I)
Sensitive AND strongly connected

(III)
Insensitive but strongly connected

(II)
Sensitive but weakly connected

(IV)
Insensitive AND weakly connected

MLEO Sensitivity [lbs]

Risk Sensitivity

Degree of Connectivity

Degree of Connectivity

© Ed Crawley MIT
### Decision Space

<table>
<thead>
<tr>
<th>Wing Vertical Location</th>
<th>High Wing</th>
<th>Mid Wing</th>
<th>Low Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Shape</td>
<td>Rectangular</td>
<td>Tapered</td>
<td>Delta</td>
</tr>
<tr>
<td>Passive Control Shape</td>
<td>Dihedral</td>
<td>Anhedral</td>
<td>Straight</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Piston Prop</th>
<th>Turboprop</th>
<th>Turbofan</th>
<th>Turbojet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Engines</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Engine Location</td>
<td>Inside Vertical Tail</td>
<td>Side of fuselage aft of wing</td>
<td>Under Wing</td>
<td>Above Wing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical Location</th>
<th>Fuselage (Inverted-T)</th>
<th>Vertical Tail (T-Tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Swept back</td>
<td>Tapered</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Landing gear Arrangement</th>
<th>Single Main</th>
<th>Tail Dragger</th>
<th>Tricycle</th>
<th>Tricycle w/ triple body gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of stowed landing gear</td>
<td>In the Wing</td>
<td>Wing Podded</td>
<td>In the Fuselage</td>
<td>Fuselage Podded</td>
</tr>
</tbody>
</table>

Includes 157 production 30+ seat civil transports since the DC3 (in 45 distinct architectures)
Decision Space View: helps us understand key decisions

- Sensitivity is based on real historical data for a metric that includes fuel efficiency, $T/W$, $V_{cruise}$, price
Concept - Definition

• A product or system vision, idea, notion or mental image which maps Function to Form
• Embodies principle of operation
• Includes an abstraction of form
• Concept rationalizes the structure of the architecture (Imrich)
• Establishes the solution-specific vocabulary - it is the beginning of the architecture
Concept Exploration - Transporting

- Concepts vary by the assignments of the principle internal functions to form

<table>
<thead>
<tr>
<th>Function:</th>
<th>Internal Function:</th>
<th>Form</th>
<th>Form 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transporting payload</td>
<td>Lifting</td>
<td>Wheels</td>
<td>Wing</td>
</tr>
<tr>
<td></td>
<td>Propelling</td>
<td>Wheels</td>
<td>Air breathing engine</td>
</tr>
<tr>
<td></td>
<td>Guiding</td>
<td>Wheels</td>
<td>TE surfaces</td>
</tr>
</tbody>
</table>

Passengers

Lifting

Propelling

Guiding
# Exercise: Concepts

<table>
<thead>
<tr>
<th>Delivered process</th>
<th>Internal processes</th>
<th>Instrument</th>
<th>Car</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transporting</td>
<td>Lifting</td>
<td>Wheels</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wings</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Propelling</td>
<td></td>
<td>Propeller</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closed hull</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Guiding</td>
<td></td>
<td>Wheels</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Ground”</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rudder/TE</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propeller</td>
<td></td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Concept
Concept to Architecture

- Concept is a system vision, which maps Function to Form
- Contains first level functions and form

- Architecture includes the details of the assignment of function to form
- Process flow, internal operands, internal processes, interface definition
Concept of Operations of the Aircraft (left) and of the Service of Air Transportation (right).
Decomposition of Function

- Successive decomposition from 1 to 28 functions
- Ordered roughly by sequence
- Only one level 2 function is “transporting passenger”
- Is this a good decomposition?

<table>
<thead>
<tr>
<th>Level 0</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ticketing</td>
<td>linking learning reserving purchasing amending</td>
<td></td>
</tr>
<tr>
<td>checking in</td>
<td>arriving airport issuing checking inspecting examining alerting changing</td>
<td></td>
</tr>
<tr>
<td>loading</td>
<td>loading embarking storiing</td>
<td></td>
</tr>
<tr>
<td>transporting</td>
<td>informing entertaining nourishing</td>
<td></td>
</tr>
<tr>
<td>transporting</td>
<td>conveying shipping evacuating</td>
<td></td>
</tr>
<tr>
<td>unloading</td>
<td>collecting disembarking unloading</td>
<td></td>
</tr>
<tr>
<td>checking out</td>
<td>collecting departing airport crediting</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1 function</th>
<th>6 functions</th>
<th>28 functions</th>
</tr>
</thead>
</table>

© Ed Crawley MIT
Creating the Final Level 1 Architecture

• The final level 1 architecture is not found by working down to level 1 from level 0, but working up from level 2

• “2 down, 1 up”

• Start with the system at level 2

• Find appropriate modularization at level 1

• That will balance all of the important considerations and (hopefully) find that they cleave along the same “planes”
- This is modularization by functional interaction
- Must also consider from, integration, legacy, suppliers, etc.
- Good modularization is a key step to making complex systems less complicated
JOURNEY TO MARS

- HUBBLE
- INTERNATIONAL SPACE STATION
- SPACE LAUNCH SYSTEM (SLS)
- ORBITERS
- LANDERS
- PHOBOS
- DEIMOS
- ORION
- SOLAR ELECTRIC PROPULSION
- ASTEROID REDIRECT MISSION
- IN-SPACE HABITAT
- MARS TRANSFER SPACECRAFT

MISSIONS:
- EARTH RELIANT: 6-12 MONTHS, RETURN: HOURS
- PROVING GROUND: 1 TO 12 MONTHS, RETURN: DAYS
- EARTH INDEPENDENT: 2 TO 3 YEARS, RETURN: MONTHS
Augustine Human Space Flight Committee 2009: Stakeholder Based Evaluation Measures

<table>
<thead>
<tr>
<th>Evaluation Measure</th>
<th>Traceability</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Space Act</td>
<td>VSE 2004</td>
</tr>
<tr>
<td>Exploration Preparation</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Technology Innovation</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Science Knowledge</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Expanding Human Civilization</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Public Engagement</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Economic Expansion</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Global Partnership</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Decisions that Frame Policy

1. What is the phase out plan of the Shuttle?
   – As planned in 2012, extend?
2. What is the future of the ISS?
   – End in 2015, extend to 2020?
3. What is the strategy for exploration beyond LEO?
   – Moon first, flexible
4. Should the government developed launch system be based on:
   – NASA Ares, Ares lite, direct shuttle derivative or an EELV heritage systems?
5. How should crew be carried to LEO (ISS in particular)
   – Commercial or US Government supplied
High Level Decision Evolution of the Committee

Starting Point

ISS

Moon

Flexible Path

Mars

ISS

Moon

Flexible Path

Mars

ISS

Moon

Flexible Path

Mars

ISS

Moon

Flexible Path

Mars

ISS

Moon

Flexible Path

Mars

ISS

Moon

Flexible Path

Mars
Suggested Integrated Option Decision Analysis

Constrained to the budget?

Constrained

Less Constrained

Content?

PoR

ISS+ to 2020

Option 1

Option 2

Strategy?

Launch system?

Moon First

Launch system?

Flexible Path first

Ares V

Option 3

Ares V Lite

Option 4A

SDV

Option 4B

Moon

ISS+

ISS+

ISS+

ISS+

Flexible Path

Flexible Path

Flexible Path

Ares V Lite

Option 5A

EELV derived

Option 5B

SDV

Option 5C

ISS+
The Flexible Path (with Ares V Lite) dominates the Baseline:

- Exploration preparation (much more capable launch system)
- Technology (investment)
- Science (more places visited)
- Human civilization (ISS extension)
- Economic expansion (in space commercial elements and crew)
- Global partnerships (ISS)
- Public engagement (more new things)
- Schedule (out of LEO sooner)
- Life cycle costs

This is a significant difference in benefits for the same investment!
Outcomes

• Developed a rigorous engineering discipline with design principles, semantically exact ISO approved notation, and some ability to compute

• Applied successfully to technical systems of wide variety

• Educated thousands of young and mid career professionals

• Created texts and online education
References