iRobot Reliability Program and Practices

ASQ Boston
Jan. 19, 2012
Agenda

• Brief Introduction of iRobot Corp.
• iRobot PLCM and Reliability Engineering Milestones
• Reliability Design, Analysis, and testing Technologies Used in iRobot Product Design
• Reliability Parameters used in iRobot Reliability Program
• Method to Determine Reliability Requirements for iRobot Product
• Reliability Allocation
• Case Study and Examples
iRobot

Robots That Make A Difference

• Leader in developing practical robots for consumers, researchers, first responders and the military

• Founded in 1990
• 2010 Revenue - $401 million
• Stock trades on the NASDAQ stock market (IRBT)
• Approximately 650 employees

• Corporate headquarters located in Bedford, MA, USA
• Other US offices in California, Washington, DC, Michigan and North Carolina
• International offices in the United Kingdom, India and Hong Kong
iRobot Government and Industrial Robots

Protecting Those In Harm’s Way

• Unmanned Ground Vehicles (UGVs) perform dangerous search, reconnaissance and bomb-disposal missions
  – PackBot, SUGV, FirstLook, Warrior

• More than 4,000 robots have been delivered to military and civil defense forces worldwide

• Unmanned Underwater Vehicles (UUVs) perform a variety of missions for maritime researchers and military planners
  – Seaglider, Ranger

• Aware 2.0 robot intelligence software allows for third-party development and modular payload integration
iRobot Home Robots

Less Chores. More Life.

• iRobot’s home robots tackle dull, dirty and dangerous jobs throughout the home

• More than 6 million home robots have been sold worldwide

• Products include:
  – iRobot Roomba Vacuum Cleaning Robot
  – iRobot Scooba Floor Washing Robot
  – iRobot Looj Gutter Cleaning Robot
  – iRobot Verro Pool Cleaning Robot
PLCM Process At-a-Glance

Idea screening and filtering

Core NPD process

Ongoing life cycle management

Industry NPD process

Idea Screen

Concept

Planning

Design

Development

Qualification

Production

Steady State

EOL

Production Start

Launch
NPD Objectives by Phase

**Concept**
- Assess business case and technical feasibility
- Commit resources for planning work

**Planning**
- Establish Plan of Record (Features, Schedule, ROI)
- Form team for implementation

**Design**
- Design concepts verified through analysis and prototype builds
- Product ID and user interface defined

**Development**
- Design meets criteria for release
- Process development is complete

**Qualification**
- Release product for volume production and shipment
- Confirm readiness to launch, sell and support the product

**Production**
- Achieve volume production
- Ongoing product life cycle management
## NPD Process – Key Milestones of Reliability Engineering

<table>
<thead>
<tr>
<th>Concept</th>
<th>Planning</th>
<th>Design</th>
<th>Development</th>
<th>Qualification</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>P / EP- RGT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Tracking and Resolution Mgmt</td>
<td></td>
<td></td>
<td>P – Dev. Test</td>
<td>EP – RGT/DVT</td>
<td>PP - PVT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PS - ORT</td>
</tr>
</tbody>
</table>

**Reliability Assessment/Monitoring**

- **MRD released**
- **PRD released**
- **Systems Eng Spec released**

**Legend:**
- MRD = Marketing Reqt Doc
- PRD = Product Reqt Doc
- P = Prototype
- EP = Eng Prototype
- PP = Pre-Production / Pilot
- PS = Production Start
- RGT = Reliability Growth Test (life)
- PVT = Process Validation Test
- ORT = Ongoing Reliability Test (life)

First around of Reliability Allocation, and start reliability design and analysis

Module Reliability Test Start
Why Reliability Engineering

- No industry can progress effectively without the knowledge and implementation of reliability engineering.
- Impact the profits of company: reputation, warranty cost, etc
- Reduce customers’ operation and support cost.
- Reduce Life Cycle Costs.
- Affect obtaining new contracts.
- Improve safety, etc.

<table>
<thead>
<tr>
<th></th>
<th>AN/ARN-21B (Old Model)</th>
<th>AN/ARN-21C (New Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failures/1,000 hr (1 year’s operation)</td>
<td>57.2</td>
<td>6.66</td>
</tr>
<tr>
<td>Maintenance costs/1000 hr per set</td>
<td>$8,000</td>
<td>$935</td>
</tr>
<tr>
<td>Maintenance cost per year per 10000 sets</td>
<td>$80,000,000</td>
<td>$9,350,000</td>
</tr>
<tr>
<td>Total savings in maintenance and support costs per year</td>
<td>$70,650,000</td>
<td>$70,650,000</td>
</tr>
</tbody>
</table>

So, we should have

**PRIDE = Put Reliability In Daily Efforts**

**iRobot = Is Reliability-design Overlooked Because Of Testing?**
Reliability Engineering – Reliability Design Technologies

Facts from reliability perspective:

- Reliability is a design characteristic, it can only be improved by design, nothing else”.
- Testing can help to find design weak points, but only design change can improve reliability. That is why reliability growth testing is considered as a TAAF process, meaning, Test, Analysis, And Fix.

- Design Criteria/Guidelines – This could be from lesson-learned or other sources, normally in the form of question.
- Part, material selection and control
- Derating
- Thermal design
- Redundancy design
- Reliable Circuit Design
- Environment Design
- Human factor design
Reliability Engineering – Reliability Design Technologies

Example of Reliability Design Criteria:

• Have parts been selected to meet reliability requirements?
• Have limited-life parts been identified, and inspection, and replacement requirements specified?
• Have critical parts which required special testing, handling been identified?
• Have stress analyses been accomplished?

Mechanical Design
• Deterministic Design
• Probabilistic Design
Reliability Engineering – Design Technologies

The basic theory of Probabilistic Design

occurs when the stress exceeds the strength.
Reliability Engineering – Analysis Technologies

The commonly used Reliability Analysis Technologies include:

• FME(C)A – Failure Mode, Effect, (Criticality) Analysis.

• FTA (Fault Tree Analysis)

• Common Cause Analysis – This method is used to identify and analyze the common cause failures, for example, power supply failure, engine explosive, etc.
Reliability Engineering – Analysis Technologies

![Diagram of reliability analysis process]

**Failure Modes (Xi):**
- $X_c$: Switch $S_1$ shorted
- $X_l$: Switch $S_2$ shorted
- $X_m$: Relay $R_1$ failed closed
- $X_n$: Relay $R_2$ failed closed
- $X_q$: High leakage current
- $X_t$: Transistor $Q_2$ open
- $X_u$: Connector short to $B$+
Reliability Engineering – Analysis Technologies Example
Reliability Testing

In iRobot, we perform the following reliability testing

• Reliability Development/Growth Testing (RGT)
• Reliability Qualification Test (RQT – For Design Validation)
• Production Reliability Acceptance Test (PRAT – For Whole Product Validation)
• Environment Stress Screening (ESS)
• Accelerated Testing (RMT, HALT)
Reliability Engineering – Reliability Qualification Test

Our engineers always ask:

How do I know if the reliability requirement is met?

There are many ways to do this, at iRobot, we basically use the following two methods:

1. Run all or some of units to fail, fit the data to distribution, then, check if the reliability goal is met.
2. If there are no failures up to certain time, the test can be stopped and we can also call the test pass. In this case, a set of criteria regarding to number of failure occurs will be needed.

The first way is the preferable one.
Reliability Engineering – Production

Reliability could be decreased if the manufacturing processes are not controlled. For example

- Use low quality and reliability parts
- Inventory control and avoid to use expired parts.
- Production process out of control due to workmanship, operator errors.

If we look at again the system reliability equation, we can rewrite it as follows:

\[ R_{\text{system}} = f(\text{design, manufacturing}) = \prod_{i=1}^{n} R_{Di} \times R_{Mi} \]

This means any module reliability is equal to its designed-in reliability times its manufacturing reliability. From here, we can see manufacturing reliability is contributed to total robot reliability.
Reliability Engineering – Production

Now, let's look at the bath tub curve again.
Reliability Parameters Used in iRobot Reliability Program

As you may know that reliability is defined as the follows:

1. The probability that an item can perform *its intended function* for a *specified interval* under *stated conditions*. or

2. A duration or probability of *failure-free performance* under *stated conditions*.

This means that reliability can be expressed by two ways:
1. Based on the first definition, the reliability can be defined by probability, such as reliability at a specific time, such as at warranty.
2. Based on the second definition, the reliability can be defined by time, such as MTBF, MTTF, or normally called life.

Can you think some reliability parameters in terms of probability and time?
# Reliability Parameters Used in iRobot Reliability Program

<table>
<thead>
<tr>
<th>Probability</th>
<th>Comments</th>
<th>Time Based</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>General</td>
<td>MTBF</td>
<td>Repairable system</td>
</tr>
<tr>
<td>Basic Reliability</td>
<td>Consider all failures</td>
<td>MTTF</td>
<td>Non-repairable system</td>
</tr>
<tr>
<td>Mission Reliability</td>
<td>Only consider failure modes which have impacts on mission</td>
<td>MTBCF</td>
<td>Same as mission reliability</td>
</tr>
<tr>
<td>Conditional Reliability</td>
<td>Known the current reliability, predict future reliability</td>
<td>MTTFF</td>
<td>Only consider the first failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Median life</td>
<td>Time at 50% product fails</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MTBM</td>
<td>Only consider failure modes which cause maintenance</td>
</tr>
</tbody>
</table>
Reliability Parameters Used in iRobot Reliability Program

In iRobot, we use both to define our reliability requirements, namely, reliability at warranty and median life, but we weight the first one more heavily.

Can you think why?
Reliability Parameter Selection

Product A and C have the same reliability at 300 hr, but they have different MTBF, 551 and 1328 respectively.

Product B and C have the same MTBF, but they have different reliability at 300 hr if we assume this is product warranty period.

<table>
<thead>
<tr>
<th></th>
<th>Beta</th>
<th>Eta</th>
<th>MTBF</th>
<th>Rel at 300 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>5.04</td>
<td>600</td>
<td>551.15</td>
<td>97%</td>
</tr>
<tr>
<td>Product B</td>
<td>1.28</td>
<td>1433.7</td>
<td>1328.4</td>
<td>87%</td>
</tr>
<tr>
<td>Product C</td>
<td>2.17</td>
<td>1500</td>
<td>1328.4</td>
<td>97%</td>
</tr>
</tbody>
</table>
Reliability Parameter Selection

As you can see from reliability parameters stated above, there are a few reliability parameters can be used to determine the reliability goals/requirements for a product. This is related to the definition of failure.

In iRobot, we define failures as the follows:
1. Core failure – failures which customers cannot fix, and will cause a product return.
2. Hard failure – failures which customers can fix by replacing failure parts/components.
3. Soft failure – failures which customers can fix by just restarting the robot. We also consider a soft failure as a hard failure if it happens frequently.

So for core and hard failure, our reliability requirement is defined by reliability at the warranty, and for soft failure, the reliability requirement is defined by MTBI (mean time between interrupts)
Method to Determine the Reliability Requirement of Product

As we discussed above, our product normally use reliability at warranty and median life or MTBF as product’s reliability requirement. The question is what it should be.

• One can define it as high as possible so it never going to be met.
• One can define it unrealistically low

So the question is what is the min reliability requirements at warranty so that we can define the product’s reliability requirement is higher than that with some margins.

In iRobot, we use a cost based method to determine the reliability requirement
Method to Determine the Reliability Requirement of Product

In our model, we consider the following items against the sale prices:

- COGS of product, accessories, replaceable parts.
- Cost if a product is returned through retailers.
- Cost of part if a customer is willing to repair it.
- Call cost through customer support.
- Non-defect return probability
- Min call in average to solve a customer issue
- Shipping cost for replaceable parts.
Method to Determine the Reliability Requirement of Product

Below chart showed the cost breakdown with our simulation.
Reliability Engineering – Reliability Allocation

- **Reliability Allocation**
  - Purpose of allocation is to determine the lower level product reliability requirements based on system level reliability requirement.
  - Can be viewed as the opposite of reliability prediction.

The allocation can be performed in many ways, the only thing is to guarantee that the entire system requirement is met. For example, for the following simple system

\[
R_{system} = R_A \cdot R_B \cdot R_C
\]

The reliability requirement for unit A, B, and C can be varied, but their product should be equal to or higher than the system reliability requirement.
Reliability Engineering – Reliability Allocation

For example, if the reliability requirement for the above system is 0.98, then we can have many ways to allocate this requirement into unit A, B, and C.

<table>
<thead>
<tr>
<th>Options</th>
<th>$R_A$</th>
<th>$R_B$</th>
<th>$R_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9933</td>
<td>0.9933</td>
<td>0.9933</td>
</tr>
<tr>
<td>2</td>
<td>0.999</td>
<td>0.995</td>
<td>0.986</td>
</tr>
<tr>
<td>3</td>
<td>0.995</td>
<td>0.986</td>
<td>0.999</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The question is how do we know which one should be used, which unit should have higher reliability, which one should have lower, can they be the same?, etc.
Reliability Engineering – Reliability Allocation

Here are some rules:

1. If there is history data and system is not changed a lot in terms of technologies, then you know which one should have higher reliability, which one should have lower.

2. If in the early stage and no history data, we can use the expert rating method by considering system’s: complexity, state of art, environment, operating time, and importance, which will give us a relative order to conduct the allocation.

3. If you just want to simplify the allocation, you can allocate each subsystem have the same requirement.

4. If you want, you can use other methods, for example equal improvement method, etc.

5. You could also use failure rate, MTBF to conduct allocation.

In iRobot, we mainly use method 2 to conduct reliability allocation for our new product.

Noted: allocation should be iterated over the course of product design and development phase.
# Reliability Engineering – Reliability Allocation

Below is a portion of reliability allocation for one of our product.

<table>
<thead>
<tr>
<th>Module</th>
<th>Failure budget at the end of warranty</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump (pump on time hr)</td>
<td>0.40%</td>
<td>99.60%</td>
</tr>
<tr>
<td>Tank (cycles)</td>
<td>0.35%</td>
<td>99.65%</td>
</tr>
<tr>
<td>Fan (hr)</td>
<td>0.32%</td>
<td>99.68%</td>
</tr>
<tr>
<td>Bumper (cycles)</td>
<td>0.25%</td>
<td>99.75%</td>
</tr>
<tr>
<td>Wheel Module (not include wheel and tire)</td>
<td>0.25%</td>
<td>99.75%</td>
</tr>
<tr>
<td>CTE sensor</td>
<td>0.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>RCON</td>
<td>0.03%</td>
<td>99.97%</td>
</tr>
<tr>
<td>Main PCB (hr) (to be tested by robot life test)</td>
<td>0.05%</td>
<td>99.95%</td>
</tr>
<tr>
<td>UI (cycles)</td>
<td>0.05%</td>
<td>99.95%</td>
</tr>
</tbody>
</table>
Case Study and Example


- P3: 83% (8% Failure Probability at xx hr, 7% Failure Probability increment from xx to xx hr, 9% Failure Probability increment after xx hours)
- EP1: 60% (8% Failure Probability at xx hr, 8% Failure Probability increment from xx to xx hr, 9% Failure Probability increment after xx hours)
- EP2: 50% (8% Failure Probability at xx hr, 6% Failure Probability increment from xx to xx hr, 14% Failure Probability increment after xx hours)
- EP3: 14% (6% Failure Probability at xx hr, 6% Failure Probability increment from xx to xx hr, 36% Failure Probability increment after xx hours)
- FEP: 36% (4% Failure Probability at xx hr, 30% Failure Probability increment from xx to xx hr, 18% Failure Probability increment after xx hours)
- PP: 22% (6% Failure Probability at xx hr, 3% Failure Probability increment from xx to xx hr, 11% Failure Probability increment after xx hours)
- PS: 7% (3% Failure Probability at xx hr, 2% Failure Probability increment from xx to xx hr, 10% Failure Probability increment after xx hours)

Post production: 7% (2% Failure Probability at xx hr, 10% Failure Probability increment from xx to xx hr, 10% Failure Probability increment after xx hours)
XX Product Reliability Status

XX Product Reliability Status

Unreliability

0.000 0.250 0.500 0.750 1.000

0.000 200,000 400,000 600,000 800,000

PP Status

Zihan Wei
Robot Corporation

iRobot
XX Product Reliability Status

XX Failure Modes and Its Frequency

We do the same for hard and soft failure modes.
XX Product Reliability Status

<table>
<thead>
<tr>
<th></th>
<th>Solution A</th>
<th>Solution E</th>
<th>Solution C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>24.97%</td>
<td>11.08%</td>
<td>2.68%</td>
<td>38.73%</td>
</tr>
<tr>
<td>T</td>
<td>30.94%</td>
<td>18.64%</td>
<td>3.78%</td>
<td>53.35%</td>
</tr>
<tr>
<td>3</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>10</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>W</td>
<td>2.68%</td>
<td>1.58%</td>
<td>0.61%</td>
<td>4.87%</td>
</tr>
<tr>
<td>R</td>
<td>0.97%</td>
<td>1.10%</td>
<td>0.49%</td>
<td>2.56%</td>
</tr>
<tr>
<td>WE</td>
<td>0.12%</td>
<td>0.24%</td>
<td>0.12%</td>
<td>0.49%</td>
</tr>
</tbody>
</table>
XX Product Reliability Status

Error Code vs. Its Locations
Product Reliability Growth – Reliability at Warranty

Reliability Growth - Failure Probability at xx hr

- Planning
- Reality

iRobot
Product XX Reliability Growth - MTBI

Product MTBI Growth

[Graph showing MTBI growth over different phases: P3, EP1, EP2, EP3, FEP, PP, PS, Post Production]
Questions

Thank you