STAT COE-Report-06-2018

Implementing Rigor in Test Plans

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11 July 2018

Revised 18 September 2018

The goal of the STAT COE is to assist in developing rigorous, defensible test strategies to more effectively quantify and characterize system performance and provide information that reduces risk. This and other COE products are available at www.afit.edu/STAT.

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Table of Contents

Revision 1, 18 Sep 2018: Formatting and minor typographical/grammatical edits.

Executive Summary

In order to reduce the overall risk associated with a new system, Scientific Test and Analysis Techniques (STAT) must be incorporated throughout testing to help produce efficient, rigorous test plans and results. One of the greatest challenges of the test design process is transitioning from an abstract methodology to implementation. Test teams usually have questions like “What information needs to be in the test and evaluation master plan (TEMP)?” or “What exactly should be included in a test and evaluation strategy STAT section?” This paper discusses an approach to implement a rigorous transition from system requirement to actual test input to the TEMP. We present an example of a fictitious system (the Ratmobile) to demonstrate this implementation method and the associated worksheets (System Decomposition, STAT Planning, and Test Planning) in the appendices can be downloaded from the STAT COE website (www.afit.edu/STAT).

Keywords: TEMP, STAT, Test, and Evaluation

Introduction

Scientific Test and Analysis Techniques (STAT) are formalized methods applied to test and evaluation to ensure results are meaningful, quantifiable, and defensible. The purpose of this best practice is to demonstrate how to effectively implement STAT to develop efficient and effective test strategies. Figure 1 shows the STAT COE test design development process.

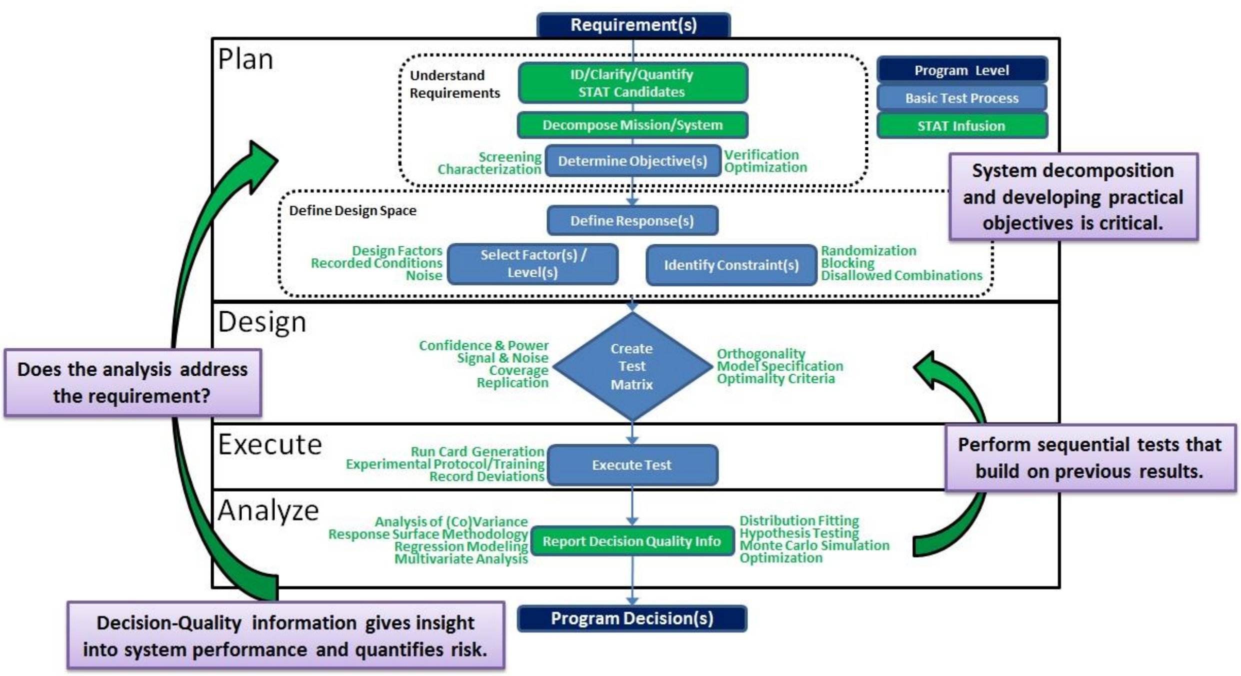

Figure 1. STAT in the Design Process Schematic

The process begins with a requirement to be demonstrated in the test. Four distinct process phases then proceed from the requirement: Plan, Design, Execute, and Analyze (Burke et al., 2017). While this method is straightforward, it can be challenging to implement due to the highly complex nature of many systems.

When implementing STAT, it is important to realize not every requirement necessitates the use of STAT. Figure 2 shows the decision process to help identify "STAT Candidates." A requirement should first be analyzed to determine if its results are deterministic or stochastic. Deterministic responses or simulations, such as "X procedure must be used" or "the weight of system X must be less than Y," can often be shown by inspection or demonstration (limited STAT required). Stochastic requirements such as "the accuracy of system X must be Y", are more likely to need more rigorous testing. Industry/military standards or community-established best practices should be used whenever applicable, as long as they are sufficiently rigorous. These usually include a moderate amount of STAT. However, when a requirement does not have an established method of testing, it is a STAT candidate. The test and evaluation process for a test should then follow the process in Figure 1.

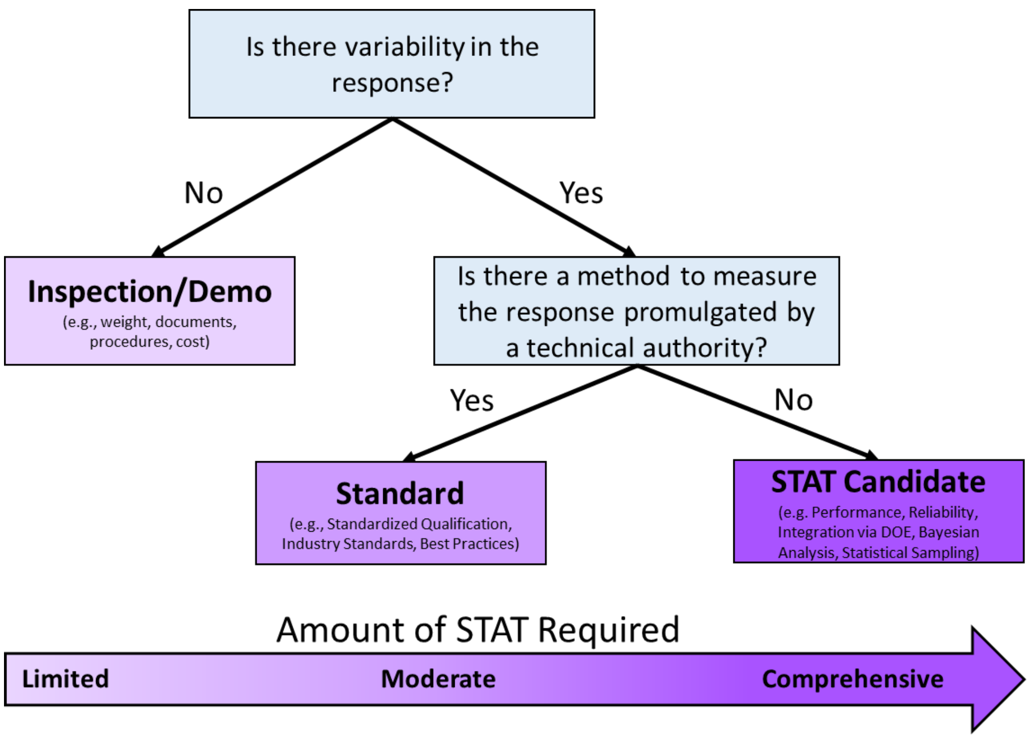

Figure 2. Decision process to identify STAT Candidates

Once the STAT candidates have been identified, the STAT test planning can begin. In the following section, we describe how to implement this process using an example: the Ratmobile.

Implementation Method

The implementation method begins by methodically decomposing a system (or sub-system) to an appropriate level so that it can be mapped to a requirement. The level of detail should be driven by requirement(s) and test objective(s). Test objectives should be specific, unbiased, measurable, and of practical consequence (Coleman and Montgomery, 1993). The design space is defined by responses measuring the requirement and by associated factors potentially affecting the responses. The factors may consist of several levels or be held constant, depending on what can be controlled in the actual test. Finally, identifying all test constraints such as disallowed combinations among factor levels, test range restrictions, or resource constraints is critical. The use of STAT continues throughout the process to include Design, Execute, and Analyze and can always be traced back to the requirement(s). The Plan phase should be the primary focus in this process because it solidifies the direction of the test process and will significantly influence later phases and outputs. We now go into each phase sub-component below.

System Decomposition

System decomposition is a series of steps used to break down the overall system or function into smaller parts (sub-systems, functions, or components). A team of subject matter experts (SMEs) should discuss and analyze the system, together with a STAT consultant, using the following steps:

1. Start with the most general view reflecting the overall purpose of the system.
2. Write down a short description of the system. Initially identify what the system is and include a brief description of what it does.
3. Break down each system into subsystems (or components).
4. Continue until the basic subsystem can't be broken down any further or when it is not possible/meaningful to decompose it any further (irreducible complexity).

The Ratmobile example showcases the implementation method and focuses specifically on the transceiver component of the Rat-a-rang subsystem. Using the System Decomposition Worksheet (Appendix A), a system decomposition diagram (Figure 3) is displayed to visually depict the Ratmobile system.

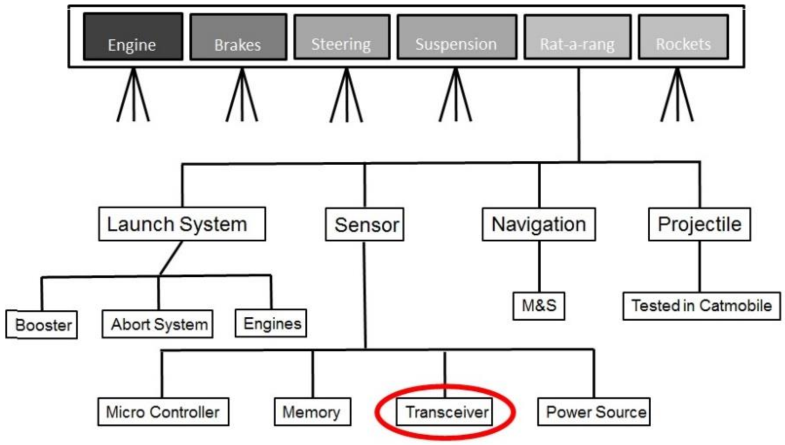

Figure 3. System Decomposition Diagram - The Ratmobile

Once the team has decomposed the system to levels of irreducible complexity, update the System Decomposition Worksheet to include those sub-systems/functions/components under evaluation. Table 1, for example, shows the sub-system description for the transceiver component of the Rat-a-rang.

Table 1. System Decomposition Worksheet – Sub-system Description

Function #	Description	Requirement (KPP, KSA, etc.)	Testable Question	Objective Type
1	Transceiver: sends/receives signals related to rat-a-rang targets			

Requirement Mapping

The team should be able to trace requirements throughout the test and evaluation process. Effective test planning starts with understanding the requirement (Harman, 2013). For each sub-system/function/component identified on the System Decomposition Worksheet, list the associated requirement to ensure its traceability from a function to a requirement. The requirement may be a key performance parameter (KPP), a key system attribute (KSA), a technical requirement, etc. Table 2 shows an update to the System Decomposition Worksheet which now identifies the specific requirement mapped to the transceiver.

Table 2. System Decomposition Worksheet – Sub-system Requirement

Function #	Description	Requirement (KPP, KSA, etc.)	Testable Question	Objective Type
1	Transceiver: sends/receives signals related to rat-a-rang targets	KPP1		

Objective/Testable Question

Well-defined test objectives must be specific, unbiased, measurable, and of practical consequence (Coleman and Montgomery, 1993). Test objectives must be systematically identified and traced directly to a requirement resulting in a better test design choice and more meaningful test results (Burke et al., 2017). The objective should include an action verb which may dictate the type of testing required. A sub-system/function/component may have more than one objective. The STAT COE has found that it is often useful to phrase your objective in the form of a testable question. This way, you can define the responses so that they will directly answer the question.

Developing effective test objectives can be a challenging process. Creating a proper test objective is "difficult, collaborative, unambiguous, sequential, and iterative" (Truett, 2015). Test objectives are not always clear and typically take time to develop. SMEs and test personnel, such as engineers, range operators, and system operators, must work together to create proper test objectives. The Objective Type should also be identified. We have listed common objective types below in Table 3 (Montgomery, 2017).

Table 3. Action Statements for Objective Types

Objective Type	Action
Characterize	To measure the response across a design space
Screen	To learn which factors have the most influence on the response
Optimize	To find the factor levels that result in a desired response
Confirm	To verify the system behavior is consistent with theory or experience
Discover	To determine what happens when factors are added/removed or the factor ranges are increased
Robustness	To find the factor levels that both provide desired response, AND reduce the variance of the response

The SMEs and test personnel for the Ratmobile's transceiver team met to discuss test objectives. The team developed two test objectives in the form of testable questions for the transceiver sub-system and determined both questions informed the response across the entire design space. The updated System

Decomposition Worksheet (Table 4) lists the specific test questions to be answered; the team identified both objective types as "characterize." The team would like to know if the transceiver both meets the design specifications of performance and does so without many errors. If helpful, the team could decompose the resulting testable objective further to help identify the correct test design and bring clarity to the results. It is also possible that both questions could be answered with one single test.

Table 4. System Decomposition Worksheet – Define the Objective

Function #	Description	Requirement (KPP, KSA, etc.)	Testable Question	Objective Type
1	Transceiver: sends/receives signals related to rat-a-rang targets	KPP1	How is the transceiver transmission performance affected under different operating conditions of the rat-a-rang?	Characterize
1	Transceiver	KPP1	How is the transceiver transmission accuracy affected under different operating conditions of the rat-a-rang?	Characterize

Appendix A contains the completed System Decomposition Worksheet for the Ratmobile example along with a blank worksheet.

Responses

A response is analyzed to evaluate the test objective (Burke et al., 2017). For a given test, the team will likely want to measure more than one response to answer the objectives. Appropriate test responses are often easily identified by way of a process flow diagram. To assist in breaking down responses, we've included a STAT Planning Worksheet (Appendix B). For each response, include a description that explains the measurement used to quantify the test objective. Remember, the response must answer the testable question. It is also important to identify the data type of the response since this will affect the type or size of the test design (e.g., binary responses will require more runs). Possible data types are continuous, discrete numeric, binary, nominal, and ordinal. Continuous responses are the preferred choice whenever possible. For more information on data types, refer to Burke et al. (2017).

In the Rat-a-rang example, there are two testable questions to answer. To answer "How is the transceiver transmission performance affected under different operating conditions of the rat-a-rang?", we measure the responses "time to transmit" and "number of total detects." Time to transmit, a continuous measurement, is defined as the time to receive a signal once the transceiver is activated. Number of total detects, a discrete numeric measurement, is the number of times the transceiver detects a signal. The response "number of false detects," which is the number of times a transceiver incorrectly detects a signal, answers the testable question "How is the transceiver transmission accuracy affected under different operating conditions of the rat-a-rang?" Using this information, we updated the STAT Planning Worksheet as shown in Table 5.

Table 5. STAT Planning Worksheet – Response Section

Response	Description	Data Type
Time to Transmit	Time to receive signal when first activated	Continuous
Number False Detects	Number of times transceiver incorrectly identifies a signal	Discrete Numeric
Number Total Detects	Number of times transceiver detects a signal	Discrete Numeric

Factors

After identifying responses, potential factors should be considered. Identifying factors requires brainstorming among a cross-functional team such as a STAT working group (WG) which includes operators, test range representatives, a STAT expert, and SMEs at a minimum. For each factor, identify which response(s) the factor is associated with. In addition, the data type (similar to responses), units, design range, number of levels, experimental control, factor changes, and priority should be identified. Whenever possible, the factor data type should be continuous. This is to provide maximum information and the highest level of detail for the test analysis (Burke et al., 2017). Often, a lower level data type can be reconfigured to be a continuous data type. The number of levels a factor may be set to will likely vary from factor to factor. In many cases, two or three levels is sufficient. Experimental control identifies whether the factor will be varied in the test, held constant, recorded, or remain uncontrolled. Factor changes refer to the degree of difficulty (in time or cost) of changing a factor level. Factors that are hard to change after each test run (therefore requiring more time) require a different design and analysis technique. The sooner we identify this information in the planning stages the easier the design generation process is. Priority classifies factors into three groups: factors of primary interest (1), factors of secondary interest (2), and nuisance factors (3). This classification helps if the design size required to include all factors greatly exceeds the test budget. The STAT Planning Worksheet (Appendix B) has a section that walks through identifying factors.

In the Rat-a-rang example, several factors with potential to impact given responses are listed in Table 6. To develop this list of factors, the Ratmobile STAT WG held recurring meetings to brainstorm potential factors of interest. The WG focused its efforts to develop a list of factors with the objective to characterize the transmission performance and accuracy of the transceiver under different operating conditions. SMEs provided insight into the values of the levels of the chosen factors. The range operators noted that changing the jamming factor to on and off would be challenging to randomize in a test. Previous experience with a similar system indicated that time of day should be included in the test. Luminosity was eventually chosen to represent this factor since it is a continuous measurement for brightness. However, due to the nature of luminosity, it will not be controlled the same as the other factors. Tests will be run in daylight, starlight, and at dusk conditions with the luminosity recorded within some tolerance. Finally, it should be noted that the wind may blow faster than 60 mph, but 60 is the limit of the measuring equipment. The development of the inputs to Table 6 was iterative as the STAT WG learned more about the transceiver.

Table 6. STAT Planning Worksheet - Factor Section

Factor Name	Data Type	Response	Units	Design Range	Anticipated # of Levels	Exp. Control	Factor Changes	Priority
Distance	Continuous	1,2,3	Ft	10-100	2	Vary	Easy	1
Number Obstructions Present	Discrete Numeric	1,2,3	Count	0,1,2	3	Vary	Easy	1
Number Targets	Discrete Numeric	1,2,3	Count	1,2	2	Vary	Easy	1
Jamming	Binary	1,2,3	-	On/Off	2	Vary	Hard	1
Luminosity	Continuous	1,2,3	Lux	1-1000	3	Vary	Easy	1
Wind	Continuous		Mph	0-60	-	Record	-	-

Constraints

A critical part of the test planning process is recognizing any possible constraints associated with the test design or execution phases (Burke et al., Dec 2017). Constraints or restrictions can have a significant impact on both design options and analysis techniques. Constraints may be related to costs, schedule, the design region, facilities, or randomization to name a few.

The STAT Planning Worksheet includes an area to identify any test-related constraints to be incorporated into the TEMP. For the Ratmobile example, the range operators noted the jamming equipment takes longer to setup and increases the cost of any test run with jamming on. This limitation was annotated in the worksheet.

Table 7. STAT Planning Worksheet – Constraint Section

Constraint	Description
Jamming Equipment	Costly to implement in the test

The completed STAT Planning Worksheet for the Ratmobile example is shown in Appendix B along with a blank copy of the worksheet.

Design

With detailed planning complete, the responses, factors, and possible constraints should come together to create a cohesive picture to inform a test. Next, the STAT WG needs to determine where testing will occur. For example, testing could be in a lab, in a virtual environment using modeling and simulation, in a ground test, or in a flight test. The testing may be sequential in that initial tests will begin in the lab, then information learned from that test will be carried over into ground testing. For example, if a factor is shown not to be significant, then it could potentially be dropped from future consideration. Also, if a factor is deemed more significant than previously thought, more levels may be added. Alternatively, it may be possible to control some factors in a lab environment (such as wind or humidity), but impossible (or too costly) to control in a ground test.

In order to develop a test plan and design, it is also important to know of any other resource information such as run budget, confidence goals, power goals, or potential sequential testing. The Test Planning Worksheet elicits all of these questions which are then combined to discuss possible design strategies for testing. The STAT WG, along with the guidance of a STAT Expert, should answer these questions. The earlier the STAT Expert is included in test planning meetings, the better this process will be. You will find an example of some possible designs commonly helpful to several test objectives in Table 8 below.

Table 8. Design Types

Test Objectives	**Sample Designs***
Screening for Important Factors	Factorial, Fractional Factorial Designs, Definitive Screening Designs, Optimal Designs
Characterize a System of Process over a Region of Interest	Factorial, Fractional Factorial Designs, Response Surface Designs, Optimal Designs
Process Optimization	Response Surface Designs, Optimal Designs
Test for Problems (Errors, Faults, Software bugs, Cybersecurity vulnerabilities)	Combinatorial Designs, Orthogonal Arrays
Analyze a deterministic response (e.g., from a computer experiment)	Space Filling Designs, Optimal Designs
Reliability Assessment	Sampling Plans, Sequential Probability Ratio Test, Design of Experiments

* The design choices listed in this table are general guidelines. Select/build the design to match your goals as well as account for any restrictions in the test execution (Burke et al., 2017).

For the Ratmobile example, the completed test planning worksheet is shown in Appendix C along with a blank copy of the worksheet.

TEMP Input

STAT Verbiage

With the test strategy determined, the assembled information needs to inform the TEMP. The TEMP does not require a detailed test plan or design for every developmental or operational test. In fact, earlier versions of the TEMP will only have broad plans about what will be done and the strategy to develop those plans (for example, by following the process laid out in Figure 1). As you gain more information about the system, update the TEMP to add STAT tables and a clear strategy emphasizing the test objectives for each test event and how that test traces back to the requirements. Specifically, ensure sufficient information is contained within the TEMP to support the generation of resource requirements. While specific test designs are not required, a TEMP should include test planning details sufficient to satisfy the program's acquisition phase.

Include the more technical details such as the table of responses, factors, and constraints in an appendix of the TEMP. Table 9 provides an example of a STAT table that may be placed into a TEMP. The level of detail will increase as more information on the system is learned. This table is adaptable to fit the needs of a given system; not all testing will be done using modeling and simulation, for example. You may need to add additional columns to include development testing, integrated testing, and operational testing to show the progression of testing through the acquisition phases.

Table 9. TEMP Input - STAT TABLE

System Name	Requirement	Response	Factors	# Levels	M&S	Lab	Ground Test	Design Type Description	Notes
Rat-a-rang	KPP 1	Transmit Time	Dist	2			V	Sequential DOE to screen and augment significant factors. Expect curvature in the response.	
			Num Ob	3			V		
			Num Target	2			V		
		False Detections	…	2	V	V	V		
			…	3	V	V-HTC	H		
			…	5	V	H	H		
		Detection Rate	…	3	V	V	V		
			…	2	V	V	V		
Navigation	KSA 1	R4	F1	3		V-HTC	H	Space Filling design to cover simulation space. Validate using limited flight test points	
			F2	3	V	V	R		
			F7	4	V	H	H		
Brakes	KPP2	R5	F8	2	V	V	V		
			F9	2	V	V	R		
			F10	5	V	V	V		

Acronyms: H: hold constant; HTC: hard to change; R: record; V: vary;

The work done to develop these inputs for the TEMP, including a STAT Table like the one shown in Table 9, should not just be used for the TEMP. This information should be used to develop and create the actual test designs for each test. As the more detailed test planning documents for each test are created, this information can be used to describe more specifically how each test will be completed.

Conclusion

Test team members can use the System Decomposition Worksheet to decompose a system and develop specific, measurable, objective, and unbiased test objectives which can be traced back to specific requirements. For each test objective, a response is measured to evaluate the test objective. All responses have associated factors. Factors may be held constant (H), recorded (R) or varied (V) based on the number of levels. Document responses and factors using the System Planning Worksheet. The completed Test Planning Worksheet clearly identifies critical test design elements. Consult a STAT expert when completing this worksheet. Finally, the information from these worksheets should generate appropriate information (STAT verbiage and table) to include in your test documents. This information will also provide the more detailed information when designing specific test designs for each test event.

References

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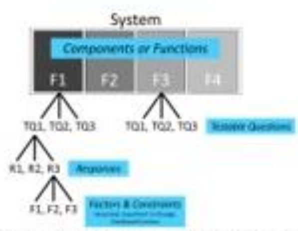
Appendix A: System Decomposition Worksheet

All worksheets can be obtained in a Microsoft word format by contacting the STAT COE at COE@afit.edu.

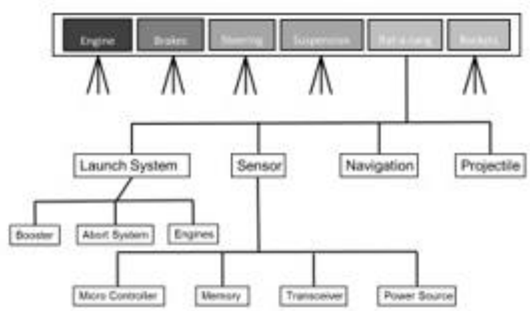
Date: ______________________________

System Decomposition Worksheet

Rat-a-Rang Transceiver



System Decomposition: Decompose your (sub)-system into its functional components



Defining the Objectives/Testable Questions: Should be specific, unbiased, measurable, and of practical consequence

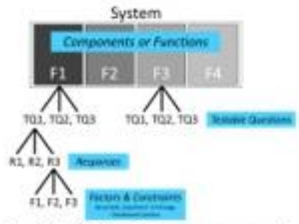
These are the testable questions you will answer by executing the test(s) on your system. Note: A function/component may have more than one test objective associated with it

Function #	Description	Requirement (KPP, KSA, etc.)	Testable Question	Objective Type
1	Transceiver: sends and receives signals related to targets of the rat-a-rang	KPP1	How is the transceiver transmission performance affected under different operating conditions of the rat-a-rang?	Characterize
1	Transceiver	KPP1	How is the transceiver transmission accuracy affected under different operating conditions of the rat-a-rang?	Characterize
2	Power Source	...	...	...
3	Micro Controller	...	...	...
4	Memory	...	...	...

Objective/Testable Question Types: Characterize, Screen, Optimize, Compare, Confirm, Discover, Robustness

Date: ______________________________

System Decomposition Worksheet



System Decomposition: Decompose your (sub)-system into its functional components

Defining the Objectives/Testable Questions: Should be specific, unbiased, measurable, and of practical consequence
These are the testable questions you will answer by executing the test(s) on your system. Note: A function/component may have more than one test objective associated with it

Function #	Description	Requirement (KPP, KSA, etc.)	Testable Question	Objective Type

Objective/Testable Question Types: Characterize, Screen, Optimize, Compare, Confirm, Discover, Robustness

Appendix B: STAT Planning Worksheet

Branch: Rat-a-Rang for Ratmobile
Function: Transceiver
Test Objective: Transceiver Performance

STAT Planning Worksheet

Rat-a-Rang Transceiver

Use the information from the System Decomposition worksheet to determine responses, factors, and constraints for each objective (the testable questions).

Identify Responses: Explain the measurement used to quantify the objective (the testable questions). The response should allow you to answer the testable question. Each response should be expected to be influenced by factors.

Response	Description	Data Type
1. Time to Transmit	Time to receive signal when first activated	Continuous
2. Number False Detects	Number of times transceiver incorrectly identifies a signal	Discrete Numeric
3. Detection Rate	Number of times transceiver detects a signal	Discrete Numeric
4.		

Response Data Types: Continuous, Discrete Numeric, Binary, Nominal, Ordinal

Identify Factors: Which variables should be explored that may have an effect on the response?

Factor Name	Data Type	Response	Units	Design Range	Anticipated # of Levels	Exp. Control	Factor Changes	Priority
Distance	Continuous	1,2,3	Ft	10-100	2	Vary	Easy	1
Number Obstructions Present	Discrete Numeric	1,2,3	Count	0,1,2	3	Vary	Easy	1
Number Targets	Discrete Numeric	1,2,3	Count	1,2	2	Vary	Easy	1
Jamming	Binary	1,2,3	-	On/Off	2	Vary	Hard	1
Luminosity	Continuous	1,2,3	Lux	1-1000	2	Vary	Easy	1
Wind	Continuous		Mph	-	-	Record	-	-

Data Type: Continuous, Discrete Numeric, Binary, Nominal; **Exp. Control**: Vary, Hold Constant, Record, Noise (Uncontrolled)
Factor Changes: Easy, Hard, Very Hard, Impossible; **Priority**: 1 = factors of interest, 2 = factors of secondary interest (not required), 3 = nuisance factors (want to minimize impact)

Identify Constraints: Test constraints, factor constraints, resource constraints, etc.

Constraint	Description
Jamming Equipment	Costly to implement in the test

Function: ____________________________
Test Objective: ____________________________

STAT Planning Worksheet

Use the information from the System Decomposition worksheet to determine responses, factors, and constraints for each objective (the testable questions).

Identify Responses: Explain the measurement used to quantify the objective (the testable questions). The response should allow you to answer the testable question. Each response should be expected to be influenced by factors.

Response	Description	Data Type

Response Data Types: Continuous, Discrete Numeric, Binary, Nominal, Ordinal

Identify Factors: Which variables should be explored that may have an effect on the response?

Factor Name	Data Type	Response	Units	Design Range	Anticipated # of Levels	Exp. Control	Factor Changes	Priority

Data Type: Continuous, Discrete Numeric, Binary, Nominal; **Exp. Control**: Vary, Hold Constant, Record, Noise (Uncontrolled)
Factor Changes: Easy, Hard, Very Hard, Impossible; **Priority**: 1 = factors of interest, 2 = factors of secondary interest (not required), 3 = nuisance factors (want to minimize impact)

Identify Constraints: Test constraints, factor constraints, resource constraints, etc.

Constraint	Description

Appendix C: Test Planning Worksheet

Date: ______________________________

Requirement: KPP1

Test Planning Worksheet

Rat-a-Rang Transceiver

What is the objective of this test?

How is the transceiver performance affected under different operating conditions of the Rat-a-rang?

(Characterize transceiver performance)

Where can you test for this objective? [e.g., lab, M&S, ground test, flight test]

Lab, ground test

Is the response of the experiment deterministic (same output for same input conditions) or random?

Random

Can you execute this test sequentially (e.g., in multiple phases)?

The test conducted in the lab does not have to be done in one shot and can be done sequentially. The ground test must be completed within the booked range time.

Are there interaction effects between factors of particular interest? Are there other model terms (e.g. quadratic effects) of particular interest?

Main effects are the primary interest, two-factor interactions desirable if possible.

Resources And Design Information	
Anticipated Total Run Budget	20
Confidence Goal [80-99% common]	95%
Power Goal [minimum 80% common]	80% for main effects
Estimated value of system noise (σ)	0.5 seconds
Desired value of δ (Signal in response to detect)	1 seconds
Signal-to-Noise Ratio (SNR) = δ/σ	1/0.5 = 2

Using the STAT Planning Worksheet and a STAT Expert, describe the planned test strategy:

Screening design in the lab test to identify significant main effects. Must use a split-plot experiment to account for jamming.

Any factors not found to be significant in the lab test will be dropped in the ground test.

Date: ______________________________

Requirement: ___________________________

Test Planning Worksheet

What is the objective of this test?

Where can you test for this objective? [e.g., lab, M&S, ground test, flight test]

Is the response of the experiment deterministic (same output for same input conditions) or random?

Can you execute this test sequentially (e.g., in multiple phases)?

Are there interaction effects between factors of particular interest? Are there other model terms (e.g. quadratic effects) of particular interest?

Resources And Design Information	
Anticipated Total Run Budget	
Confidence Goal [80-99% common]	
Power Goal [minimum 80% common]	
Estimated value of system noise (σ)	
Desired value of δ (Signal in response to detect)	
Signal-to-Noise Ratio (SNR) = δ/σ	

Using the STAT Planning Worksheet and a STAT Expert, describe the planned test strategy:
