

The Science of Failure (Systems Health Monitoring for Satellite Systems)

Diagnostics and Prognostics Group

Discovery and Systems Health Area
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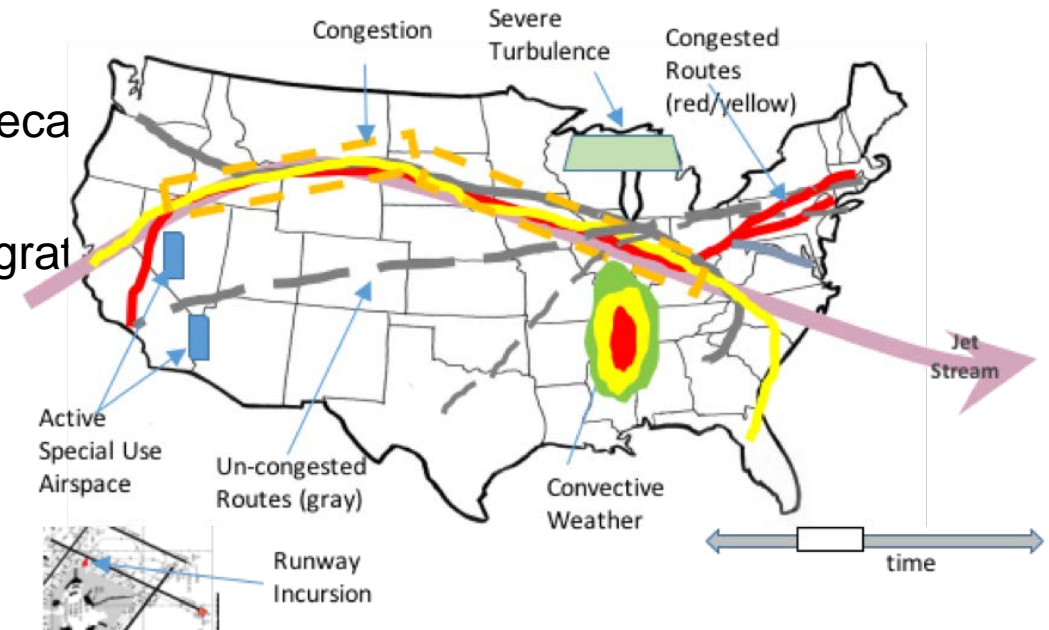
Outline

- Welcome & Introductions
- SHM Overview
- Diagnostics
 - Introduction
 - Methods
- Prognostics
 - Introduction
 - Methods
 - Case Studies
- Decision-making
 - Introduction
 - Methods
 - Case Studies
- Project overviews
- Small satellite case study

Overview: Real Time Safety Monitoring and Prediction of Unsafe Events in the National Airspace

Motivation

- National Airspace System (NAS) ensures safety through rules, regulations, and response procedures
- Air traffic in the NAS projected to increase in the near future
 - Advanced decision-making tools required to maintain the current level of NAS safety
 - Optimal decisions require knowledge of both current and future state of the NAS
- At present, different stakeholders of NAS (e.g., pilots, flight controllers) rely on their situational awareness to make informed decisions to avoid unsafe events
 - Consolidate information from disparate sources
 - Apply their domain knowledge to interpret current and forecast NAS state
 - Interact with multiple independent tools and mentally integrate the information
- Uncertainty is typically not handled in a formal and rigorous manner
- Safety assessment tools typically focus on a few threats
 - Their assessments mostly independent of other threats

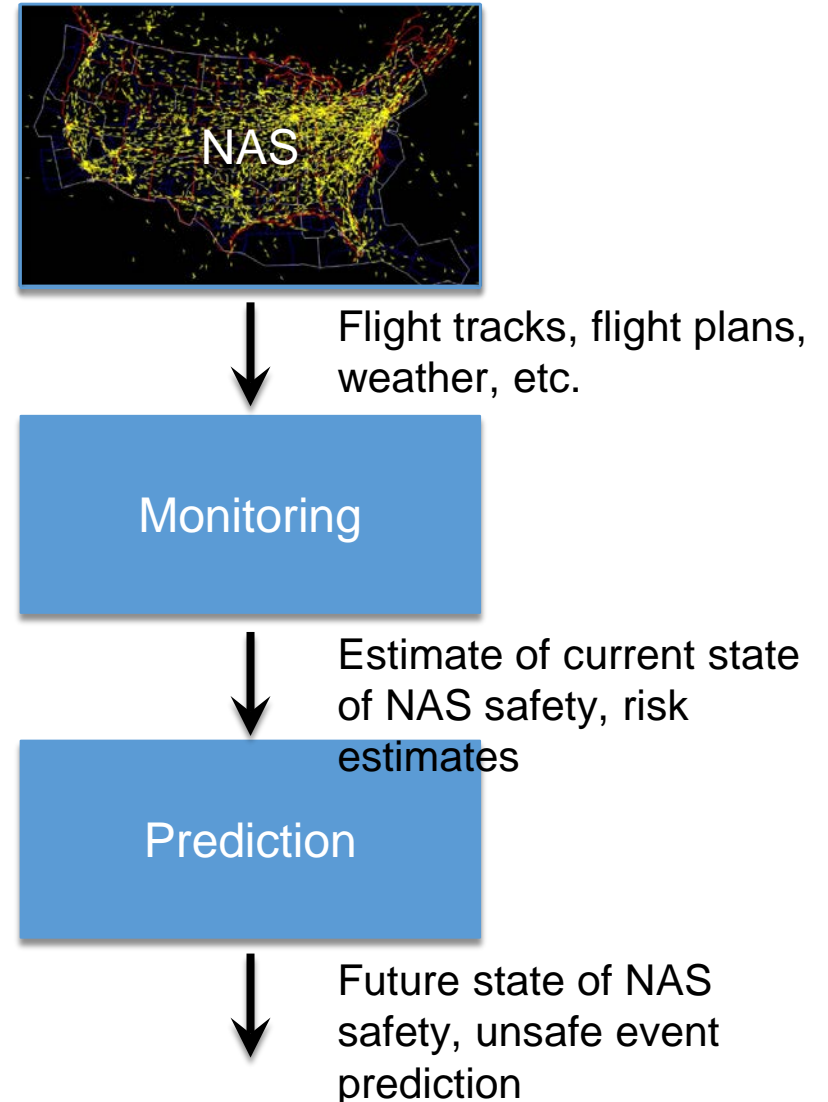


Research Goals

- Develop a framework to
 - Provide real-time assessment (nowcast and forecast) of safety and risk
 - Predict evolution of safety so as to help operators avoid unsafe states instead of needing to mitigate them
- Holistic framework
 - Combines multiple threats to safety and considers their potential interactions
 - Integrates disparate data sources
 - Incorporates multiple sources of uncertainty into the predictions
- Our solution - the **Real-Time Safety Modeling (RTSM)** framework

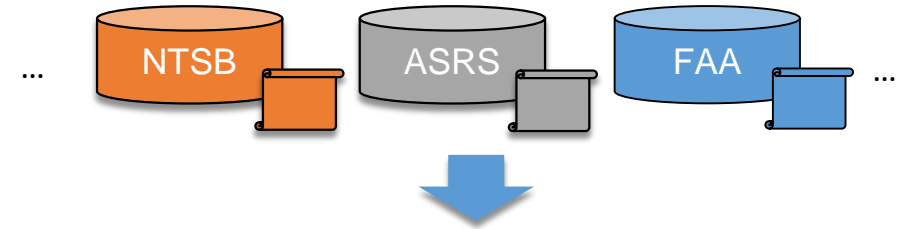
Approach

- Safety Analysis & Modeling
 - What are the hazards to safe flight?
 - What unsafe events can occur?
 - Which hazards/events occur most frequently?
- Real-Time Safety Monitoring
 - How do we define “safety” and “risk” in the NAS?
 - How do we measure/quantify it?
 - How do we estimate the current state?
- Safety/Risk Prediction
 - Which unsafe events are likely to occur in the future, if no corrective action is taken?
 - What do different NAS users need to be aware of?



Safety Analysis

- Identify hazards that compromise safety by analyzing reports from several national incident and accident databases
 - Generally categorize into *airspace*, *human performance*, and *environmental* categories
 - Down-select hazards based on potential to model, monitor, and predict
- Identify unsafe events that result from hazards



Hazards

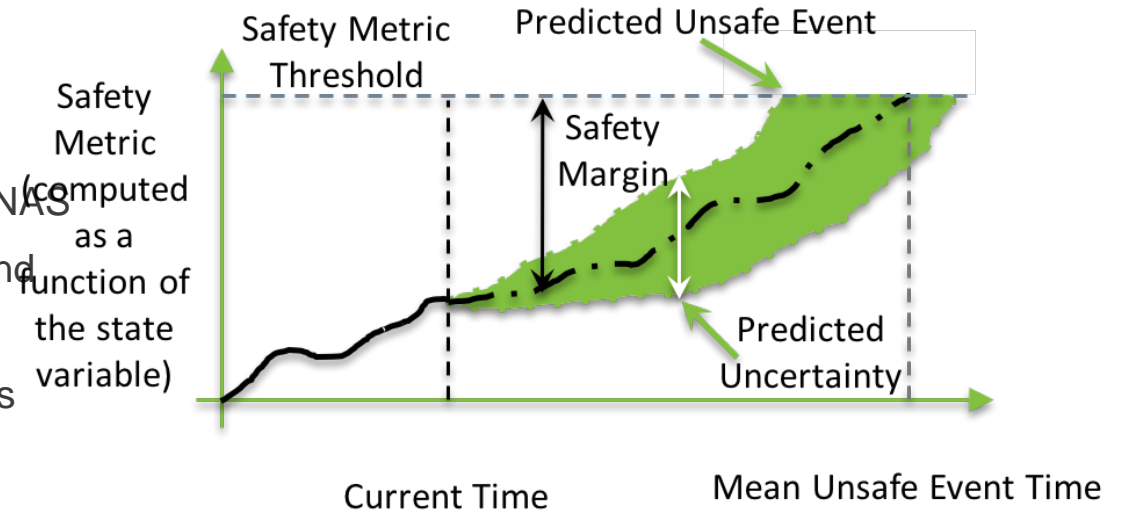
- Inoperative Navaid
- Excessive Communication
- Procedure Complexity
- Low Visibility
- Turbulence
- Icing

Events

- Loss of separation
- Evasive maneuvers
- Go around or rejected takeoff
- Unstable approach
- Convective weather encounter

Definitions

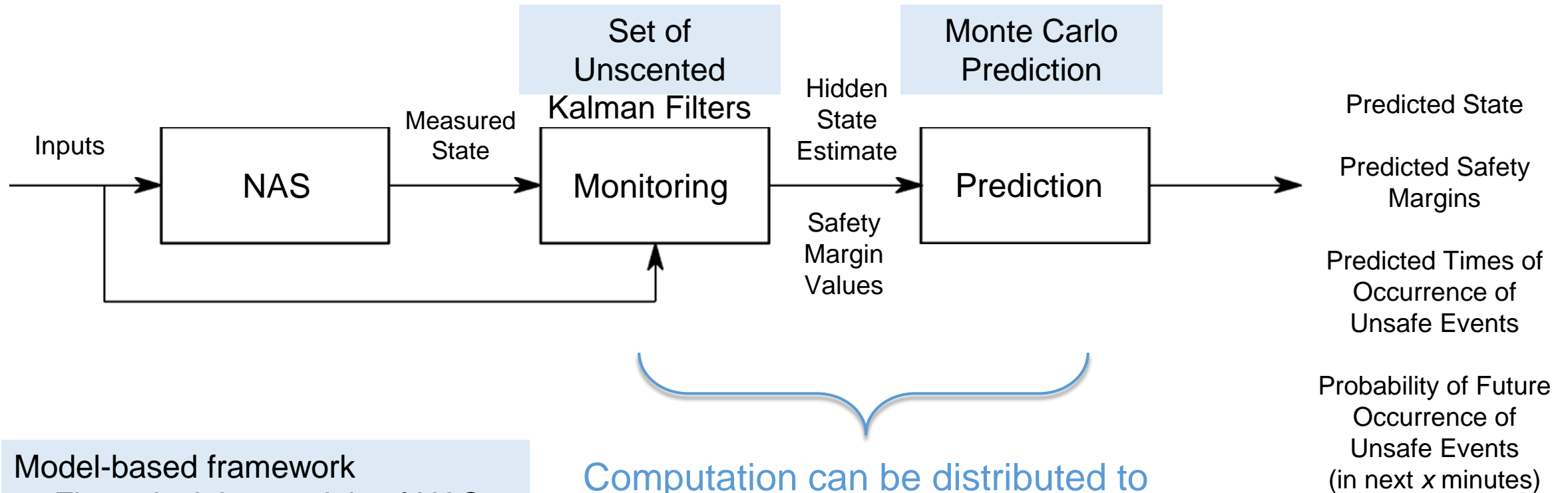
- **Unsafe event:** An event/situation that compromises NAS safety or established safety standards
 - Examples: loss of separation, loss of control, controlled flight into terrain, runway incursion, hard landing, tail strike, collision, etc.
- **Hazard:** A condition that potentially contributes to unsafe events
 - Examples: convective weather, poor visibility, difficult terrain, etc.
- **Safety metric:** A quantitative measure of some aspect of safety of the NAS
 - Examples: distance between two aircraft, distance between aircraft and convective weather region
- **Safety threshold:** Some limit on a safety metric or set of safety metrics
 - Example: Enroute separation of 5 nautical miles
- **Safety margin:** “Distance” between current safety metric(s) and safety threshold(s)



Safety Modeling

- What categories of events can occur?
 - Loss of separation, wake vortex encounter, convective weather encounter, sector demand violation, etc.
- What conditions define the occurrence of the event?
 - Defined as some function of the NAS state
 - Example 1: Loss of separation between A1 and A2 occurs when the horizontal separation is less than 5 nautical miles and the vertical separation is less than 1000 ft
 - Example 2: Sector demand is too high when the number of aircraft in a sector meets or exceeds the capacity limit
- How do we compute the safety margin w/r/t an event?
 - $\text{Margin} = \{\text{“distance” to event threshold}\} / \text{threshold}$ and expressed as a percentage
 - Therefore, Margin is 0% when event is present
- How do we compute aggregate safety margins?
 - Example: Average safety margins over all potential events

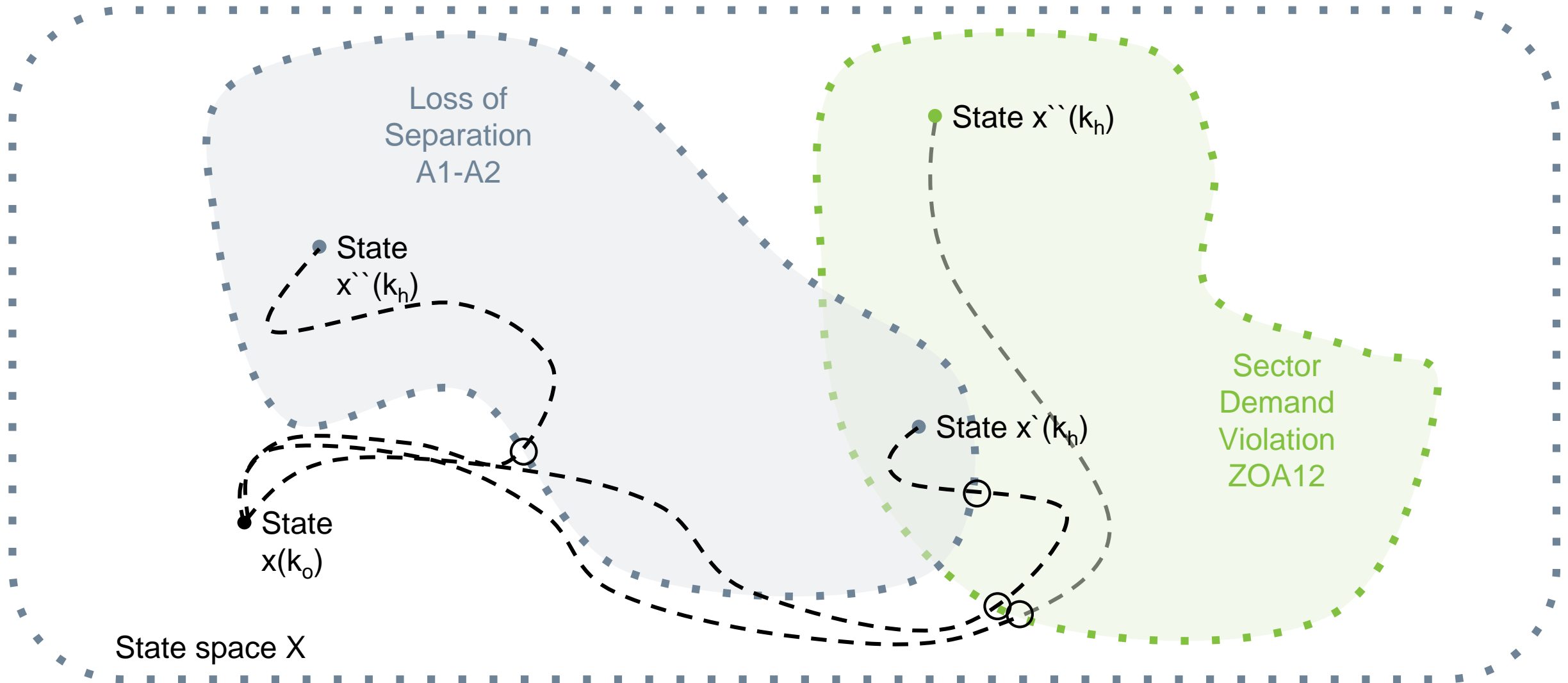
Computational Architecture



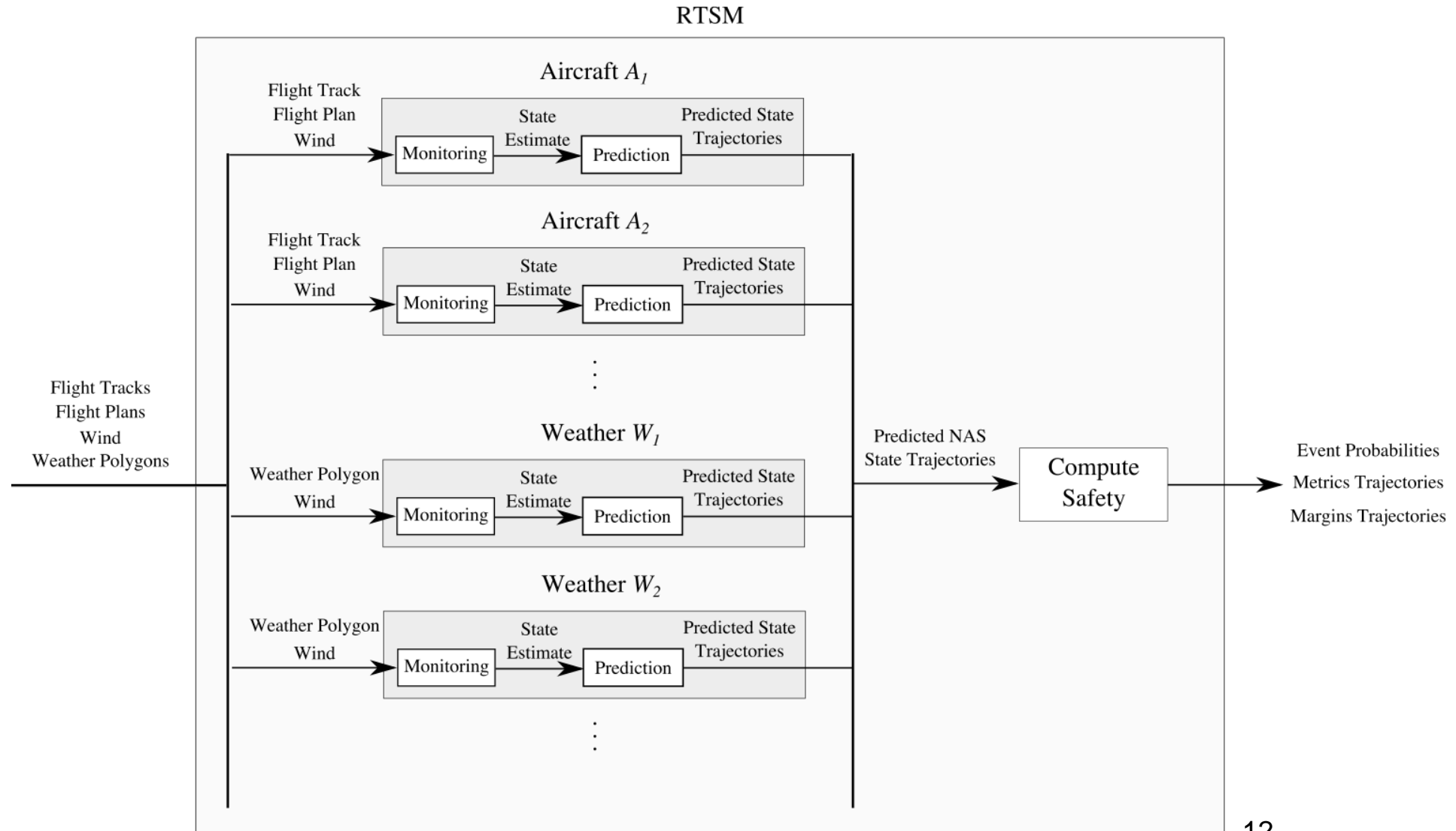
Model-based framework

- First principles models of NAS components (aircraft dynamics, weather, wake vortex, etc.)
- Safety metrics & thresholds

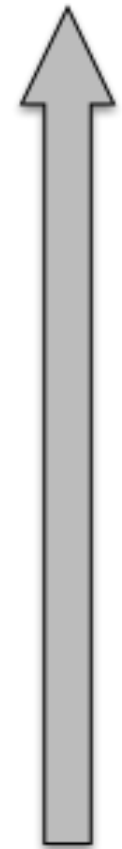
Conceptual Framework



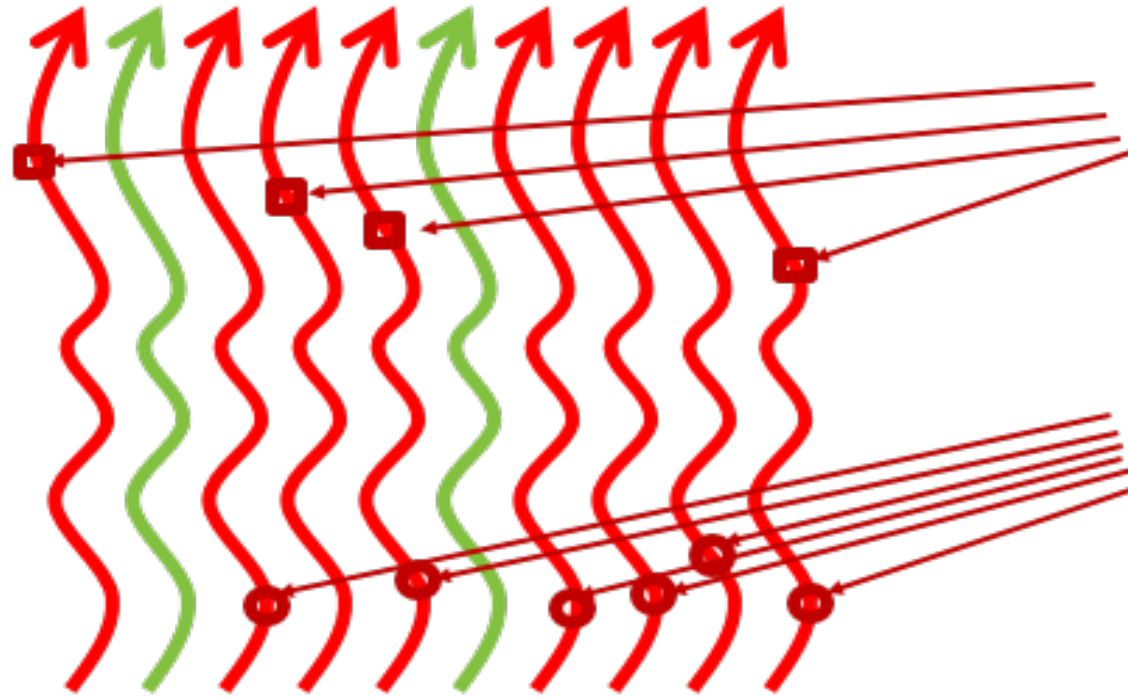
Distributed Computational Architecture



Prediction



Time



Realizations of NAS
State Trajectories

- Occurrences of $WX_{W1,A3}$:
1. Probability = 40%
 2. Time until event = 8 min. (average)

- Occurrences of $LOS_{A1,A2}$:
1. Probability = 60%
 2. Time until event = 2 min. (average)

80% Probability of Unsafe Event

Extension to Airport Surface Operations

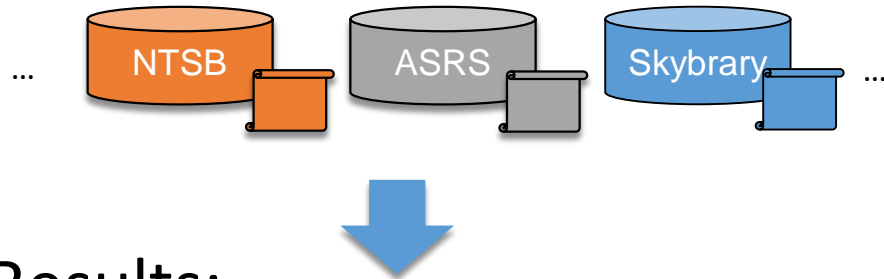
Motivation

“While commercial aviation has made extraordinary strides in safety, one area where risk remains is on the airport surface. The bottom line is planes shouldn’t run into each other in the air or on the ground.”

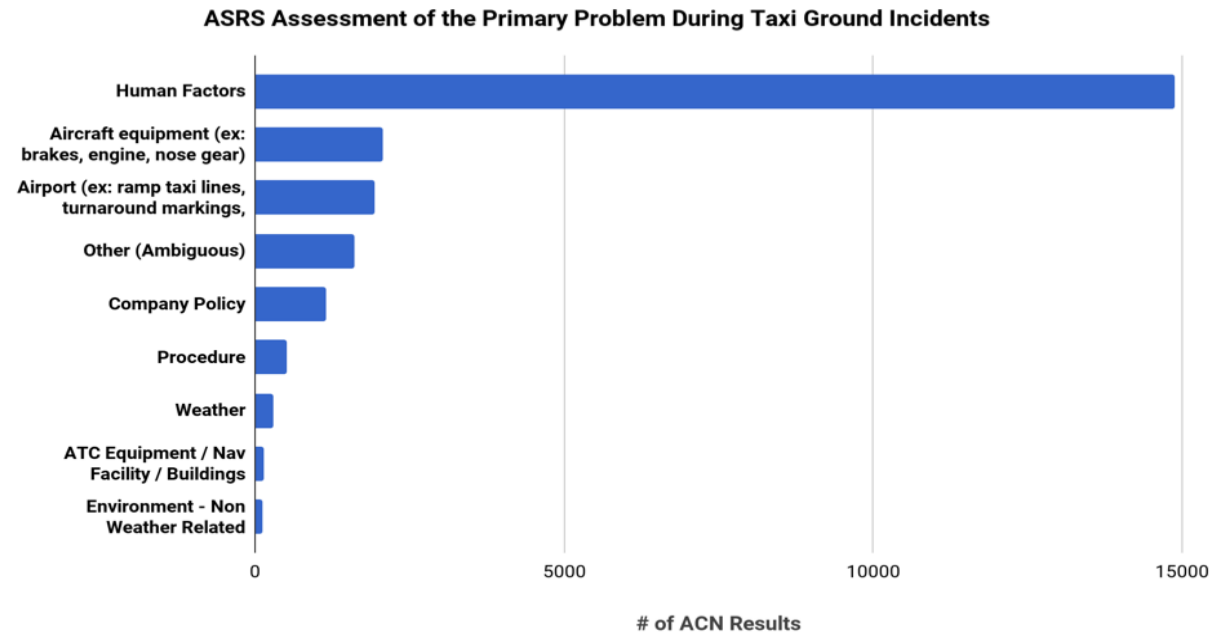
- NTSB Spokesman

Hazard Analysis

- Over 600 accident reports queried spanning multiple decades
- Flight phases: Standing, taxi, takeoff, and landing
- Locations: Ramp, taxiway, runway
- Databases: NTSB and ASRS primarily



- Results:
 - Human factors primarily
 - Weather Conditions
 - Aircraft equipment



Ground Incident Classification

- Predictable incidents:
 - Can be measured, modeled, and predicted using real-time data e.g. failure to maintain clearance from another aircraft during taxi → relevant data precursor, distance
- Unpredictable incidents:
 - Cannot be measured, modeled, or predicted using the RTSM framework¹ e.g. flight attendant tripping and falling
 - Runway incursions by foreign object
 - Failure to follow current operating standards and procedures
 - Equipment failure such as nose landing gear separation
 - Inadvertent throttle movement by flight crewmember

^[1] NTSB Report No. ERA11CA010, CHI06LA016, NYC02LA042

^[1] NTSB Report No. LAX05LA218

^[1] NTSB Report No. NYC05LA043, CHI01LA066

^[1] NTSB Report No. CHI99LA289, FTW99FA201, CHI93FA129 MIA99LA026

^[1] NTSB Report No. ENG08IA042, CHI00FA244, CHI00LA296, LAX07IA191

^[1] NTSB Report No. GEN111A270

Predictable Incidents

- Aircraft - Aircraft Ground Collisions During Taxi
 - Wingtip/Winglet impacts tail of adjacent aircraft
 - Wingtips not visible from cockpit for certain transport a/c
- Collisions During Pushback
 - Failure of tug driver to maintain clearance during pushback
 - Lack of situational awareness, inadequate visual lookout, overestimation of proximity, & lack of communication between wing walker & tug operators
- Weather-Related Incidents¹
 - Ground contamination: Snow, ice, rain, slush
 - Presence of deicers on taxiways & ramps
 - Decreased visibility

^[1] [NTSB Report No. DCA09MA021](#)

^[1] [NTSB Report No. ATL02LA029_CEN09LA093_NYC05LA038_NYC02LA056](#)

^[1] [NTSB Report No. ATL04LA053_CHI08LA051](#)

^[1] [NTSB Report No. DCA16CA070](#)

^[1] [NTSB Report No. NYC06LA074_DCA14CA051_ANC07LA008_DEN06IA008_DEN05LA048](#)

^[1] [NTSB Report No. DCA13CA035](#)

^[1] [NTSB Report No. FTW02LA088_CHI06LA092_DFW07LA155](#)

Development of Safety Metrics

- Safety Metric (SM)
- SM Function Arguments
- SM Function Outputs
- Threshold Equations
- Required Data

Safety Metrics

Safety Metric (SM)	Safety Metric Function Arguments	Safety Metric Function Outputs	Threshold Equation Example	Required Data Examples
Weather at coordinate	point of interest, time	matrix of all weather categories (e.g., precipitation, wind, temperature, etc.) and their relevant properties (e.g., type, direction, severity, persistence, etc.)	A threshold is needed for each element of the matrix. Examples: thunderstorm.began = :08, precipitation.type = ice_pellets.	Current weather; forecast weather
Surface visual range (SVR) (aka visibility)	point of interest, time, {weather at coordinate}	Distance in feet	SVR > 50 ft	As required by "Weather at coordinate" SM
Ground services operating status	Volume of interest, time	matrix of all service categories (e.g., lights, tracking coverage, runways, etc.) and operational status (e.g., Inoperative, nominal)	servicesOperatingStatus.asde_x = NOMINAL	NOTAMs
Degree of taxi route normalcy	{Airport configuration at time t}, {airport configuration at time t+5}, {probability of ramp/taxiway/runway congestion}, {surface facilities operating status}, off-nominal ops (e.g., priority aircraft, etc.)			NOTAMs (Notice to Airmen) regarding closed taxiways, standard taxi routes, expected airport reconfiguration
Taxi complexity	Taxi clearance, time, {weather at coordinate}, {degree of taxi route normalcy}	complexity category, e.g., low, medium, high	taxiComplexity < MEDIUM	Airport layout, location of hot spots, taxi clearance
Airport configuration at a given time	time, {weather at coordinate}	Runways in use, taxi routes in use		Current and forecast weather, especially wind; airport layout; standard operating procedures; traffic forecasts
Risk of aircraft collision with aircraft/vehicle/structure	position, heading, and speed of ownship, position, heading and speed of other aircraft /vehicle/structure, {probability of ramp /taxiway/runway congestion}	nearest distance (ft), risk category, e.g., none, low, medium, high	ProximityViolation = NONE	Precise position and heading; aircraft type; winglet type; aircraft dimensions; weather; airport structures location and dimensions
Probability of ramp/taxiway/runway contamination	Point of interest, time, {weather at coordinate}	probability of all contamination categories such as ice e.g., black ice, slush, etc.; water; {FOD debris}; dead animals	rwContamination.blackIce = 0	Current and forecast weather; PIREPs; runway condition reports;
Probability of vehicle loss of control on the ground (LOC-G)	point of interest, time, {probability of taxiway contamination}, {weather at coordinate}	risk category, e.g., none, low, medium, high	VehicleLOCG <= LOW	Current and forecast weather providing information about surface icing
Risk of drifting Foreign Object Debris (FOD-G)	Point of interest, time, {weather at coordinate}, FOD at nearby coordinates	risk category, e.g., none, low, medium, high	FODGRisk <= LOW	FOD existence (e.g., camera-fed image recognition)
Risk of jet blast	point of interest, time	risk category, e.g., none, low, medium, high	jetblastRisk <= LOW	Precise position and heading of all operating aircraft
Probability of ramp/taxiway/runway congestion	{airport configuration at a given time}, {weather at coordinate}, {aircraft at coordinate}	Comparison to expected congestion, i.e. low, normal, high	probCongestion <= NORMAL	Data required for the helper functions
Probability of pilot error during ground ops	Pilot id, time, {taxi complexity}, {visibility conditions}	probability in percentages	pilotErrorProb < 10%	Position and heading of aircraft, plus all the data required for the helper functions
Probability of controller error on ground ops	Controller id, time, {Ground service operating status}, {taxi complexity}, {Controller workload}	probability in percentages	controllerErrorProb < 1%	20 Data required for the helper functions

Airport Reconfiguration

Motivation

- Runway configurations depend on current and predicted traffic demand, wind speed and direction coordinated between controllers, pilots, and ground personnel
- Can be disruptive and challenging for human decision makers
- Optimization methods do not systematically handle uncertainty associated with meteorological conditions, arrival & departure demands, and other variables

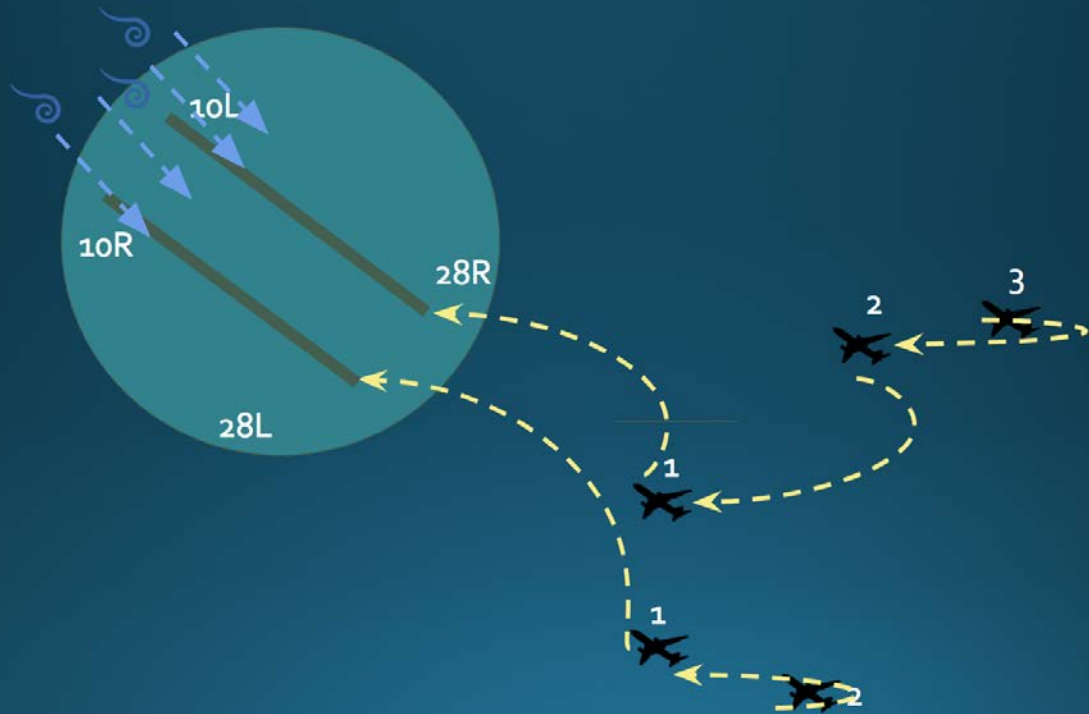
Approach: Markov Decision Process

Markov Decision Process Framework

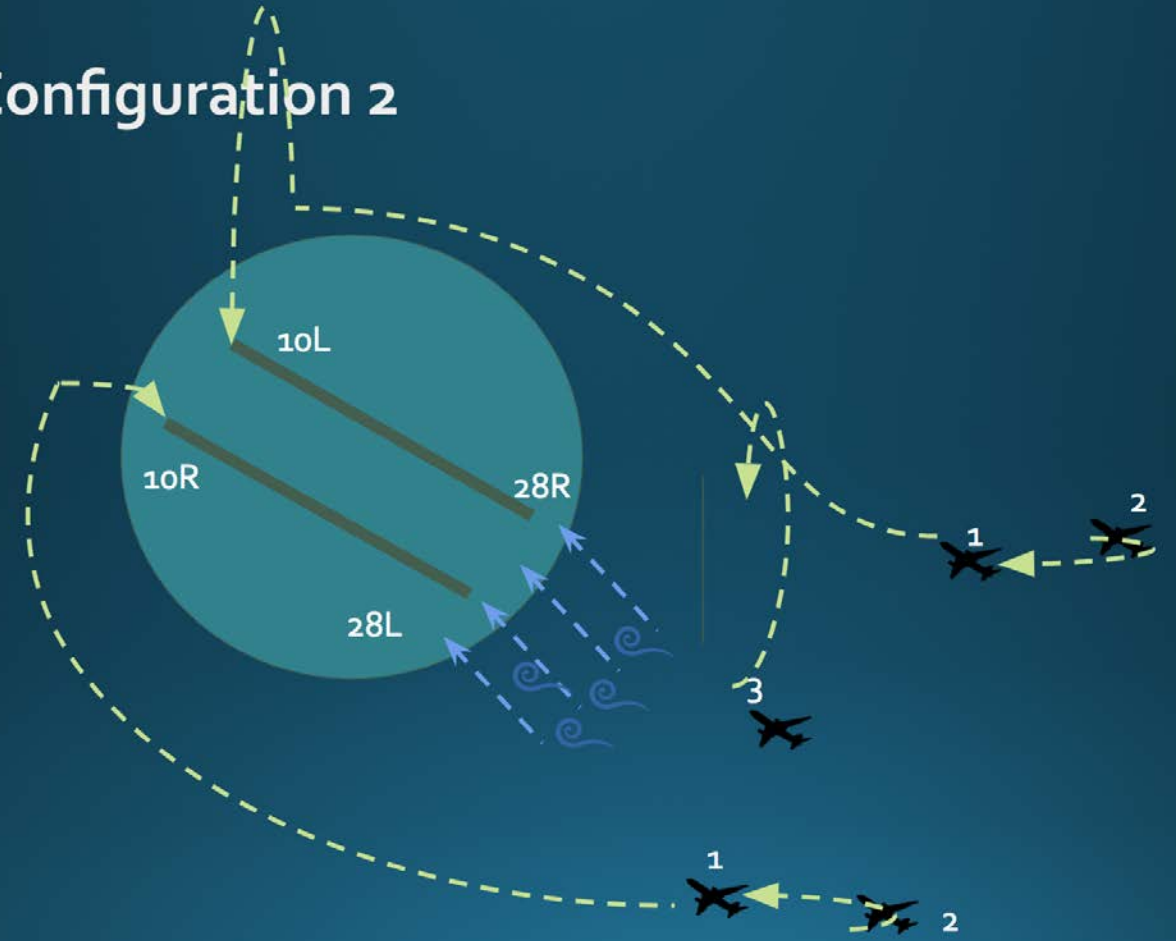
- Markov Property: The effects of an action taken in one state depend only on that state and not on the prior history.
- An MDP model is a tuple (S, A, T, R) :
 - A set of possible states S
 - A set of possible actions A
 - A real valued reward function $R(s, a)$
 - State Transition Probability Function, T
 - Uncertainty in outcome after action is taken
- Goal: Generate optimal policy using tuple instead of static planning
 - Dynamic planning with multiple step look-ahead

Reconfiguration Example

Configuration 1

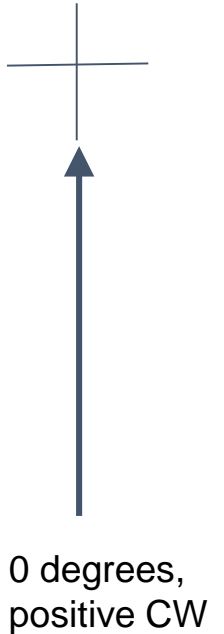
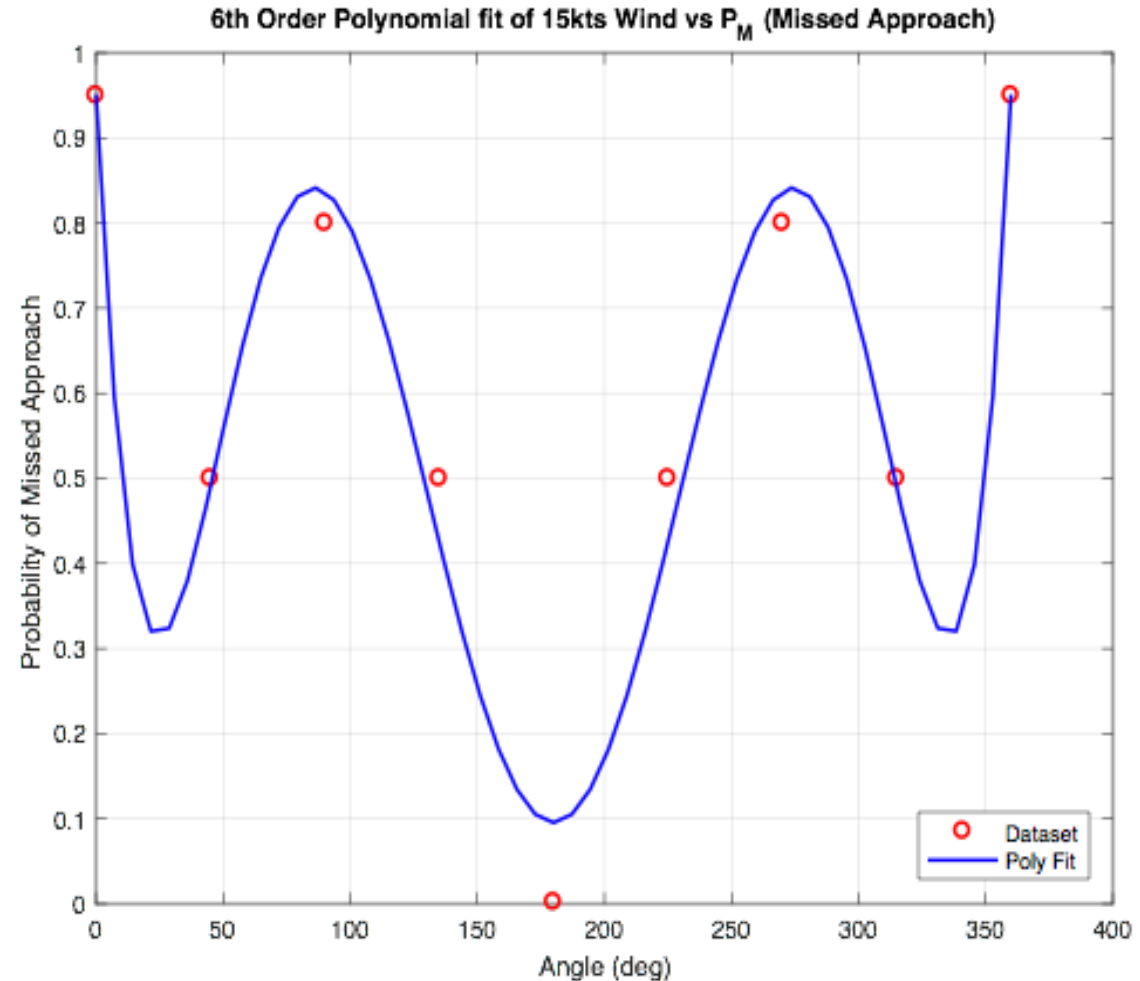


Configuration 2



MDP Elements for Runway Reconfiguration

- Using landing crosswind limit of 20 knots and tailwind limit of 15 knots
- Zero degree north
- Assume transition outside of runway is deterministic
- Transition function on runway: i.e. probability of a landing or a missed approach →



Summary Slide

- RTSM Framework for NAS Safety Monitoring and Prediction
- Airport Surface Operations
 - Hazard analysis using NTSB & ASRS databases
 - Large number of unpredictable incidents
 - Predictable incidents - may be monitored, predicted, and mitigated with relevant safety precursors using RTSM framework
- Airport Reconfiguration Problem
 - Optimal runway reconfiguration
 - Minimize frequency & handle uncertainty
 - Markov Decision Process Framework
 - Prototype implementation - Single runway, two aircraft

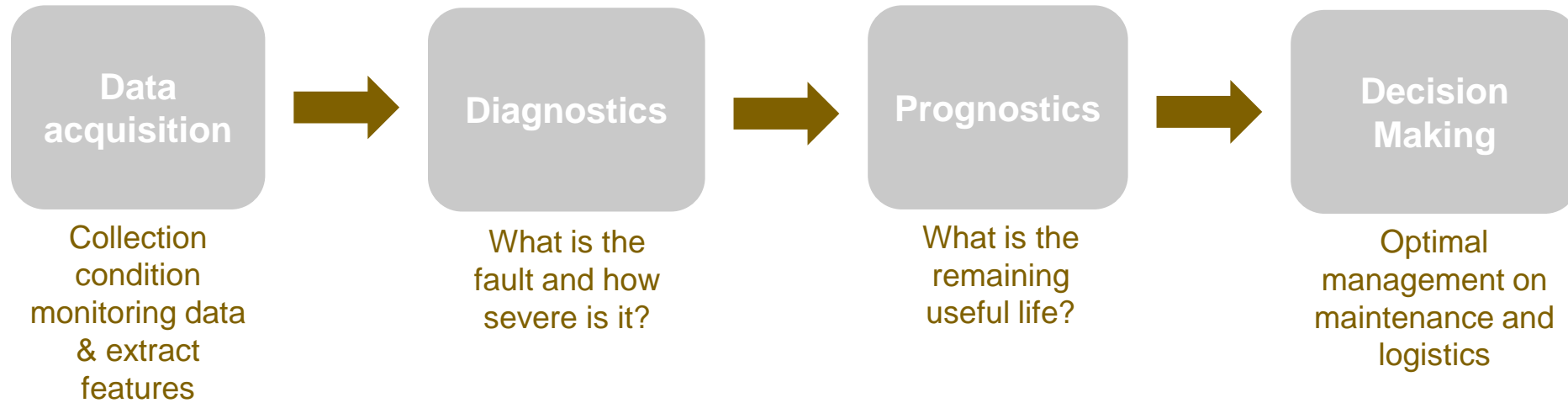
SHM for Satellites

- ❑ **System Health Monitoring**
- ❑ **Prognostic Approaches**
- ❑ **Remaining Useful Life RUL Estimation**
- ❑ **Current and Future Space Missions**
- ❑ **Goals for Satellite Missions**
- ❑ **Satellite and Systems Health Monitoring**
- ❑ **Satellite Subsystems**
- ❑ **Satellite Subsystems Anomalies and Failures**
- ❑ **Attitude and Orbit Control Subsystem**
- ❑ **Anomalies and Failures in AOCS**
- ❑ **System Health Monitoring and AOCS**
- ❑ **PHM Frame work for AOCS**

Scope

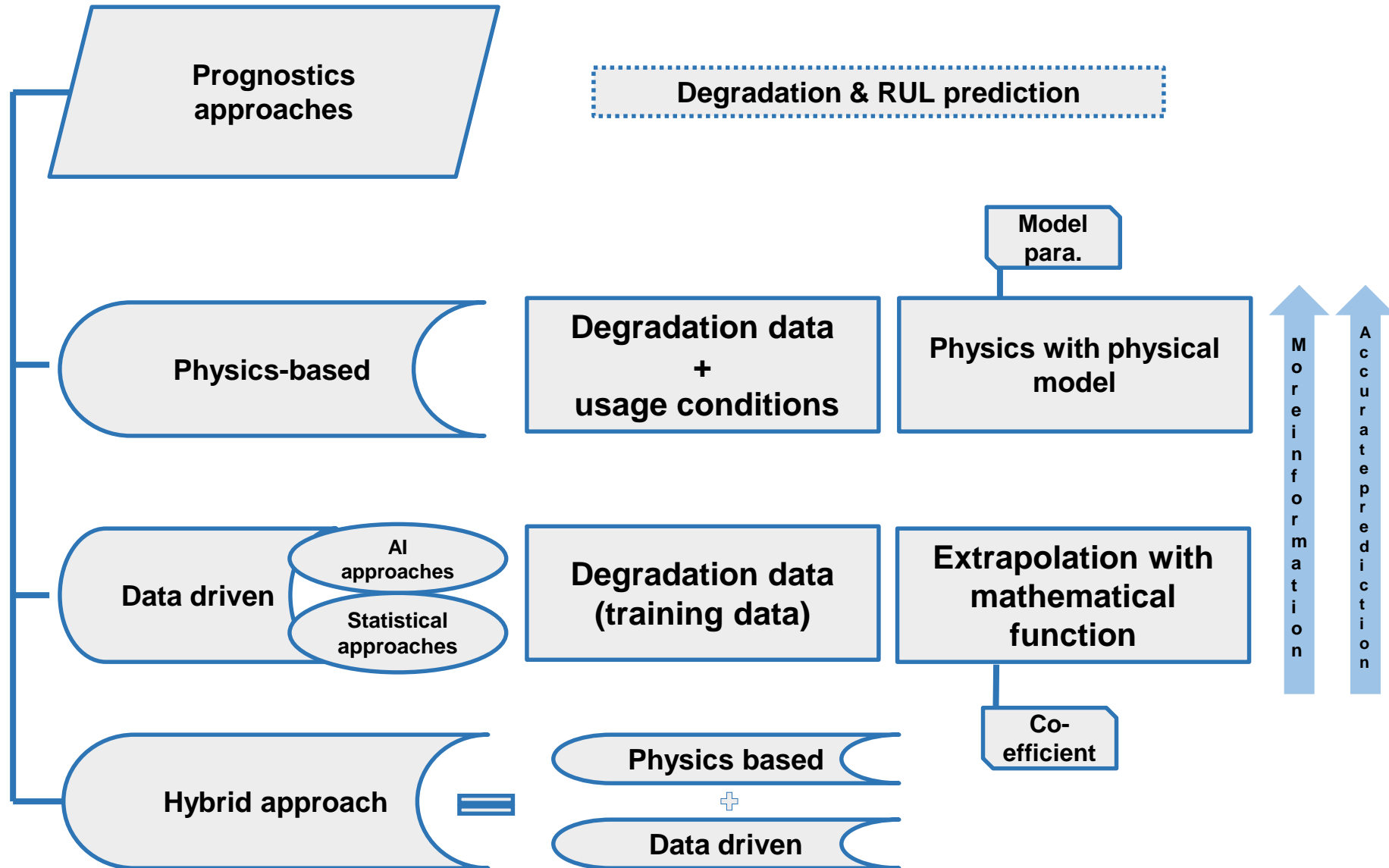
Developing a conceptual prognostics and health management (PHM) framework for small satellites in swarm formations; enabling predictions of possible failure times and the remaining useful life of the satellite(s), components and subsystems; to ultimately further autonomous exploration for space and science missions

System Health Monitoring



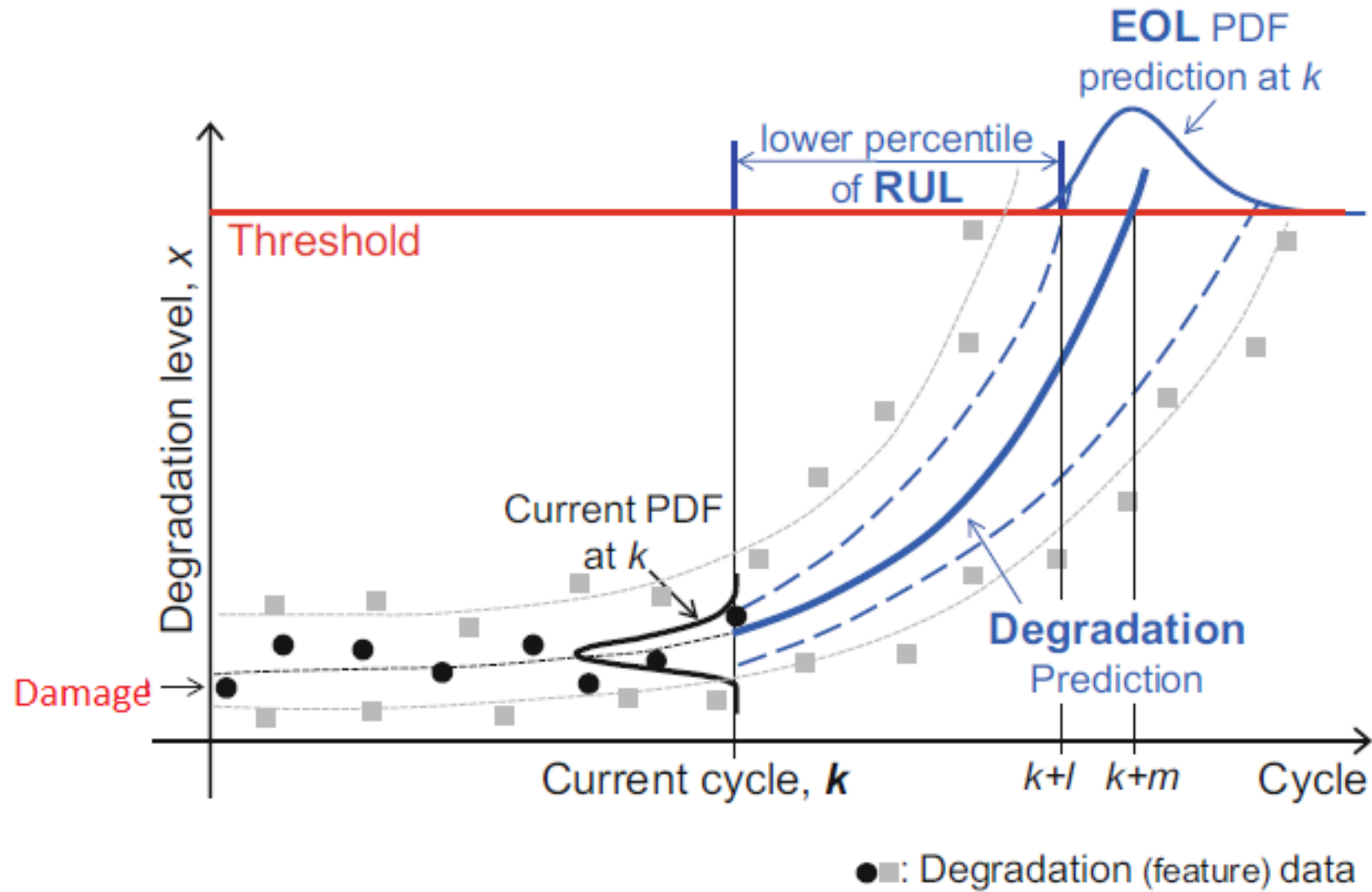
- **Prognostics** provides the decision maker an early warning about the expected time to system/subsystem/component failure

Prognostic Approaches

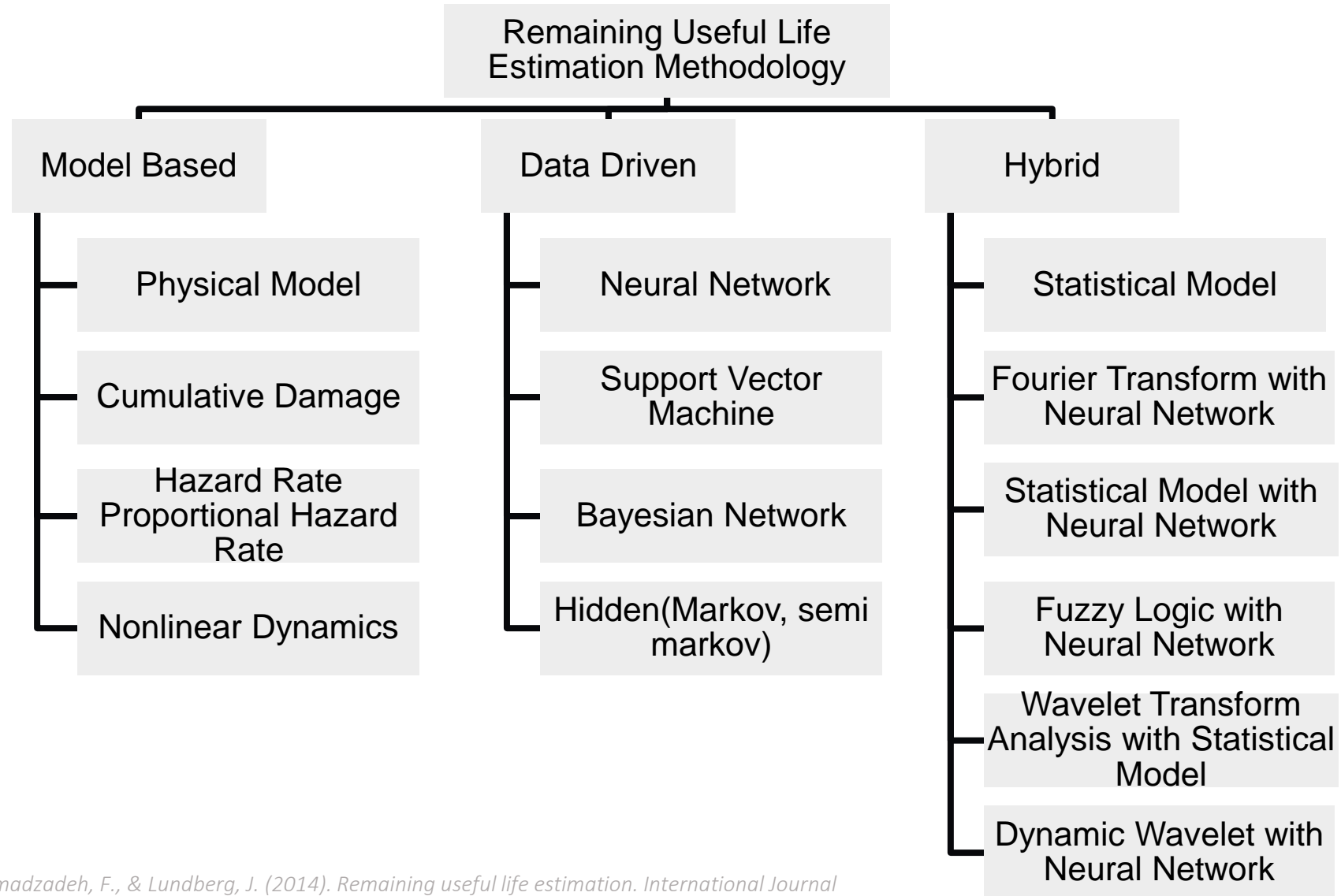


1. Kim, N.-H., An, D., & Choi, J.-H. (2017). *Prognostics and Health Management of Engineering Systems*: Springer International Publishing.

Remaining Useful Life RUL Estimation

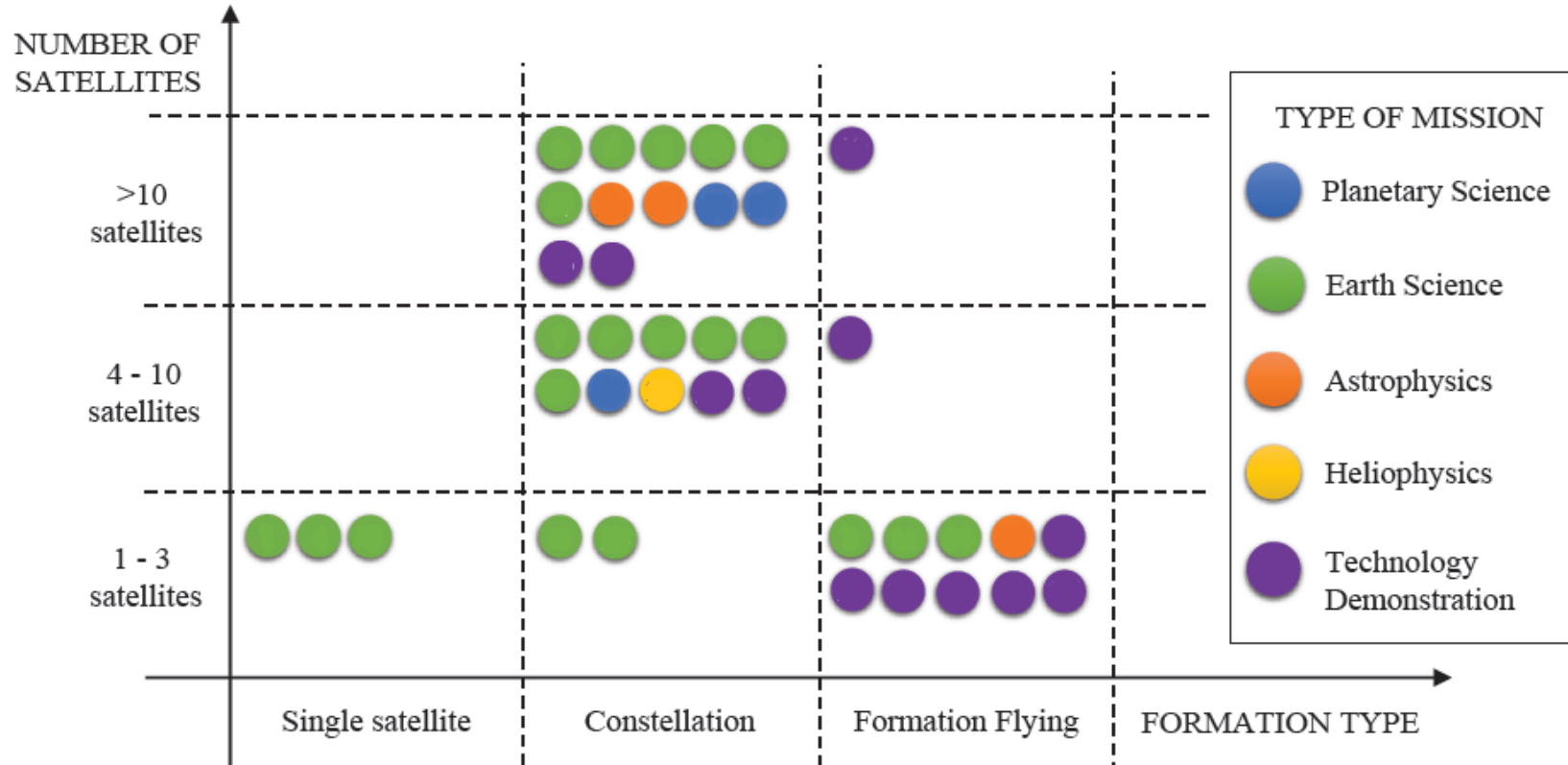


RUL Methodologies



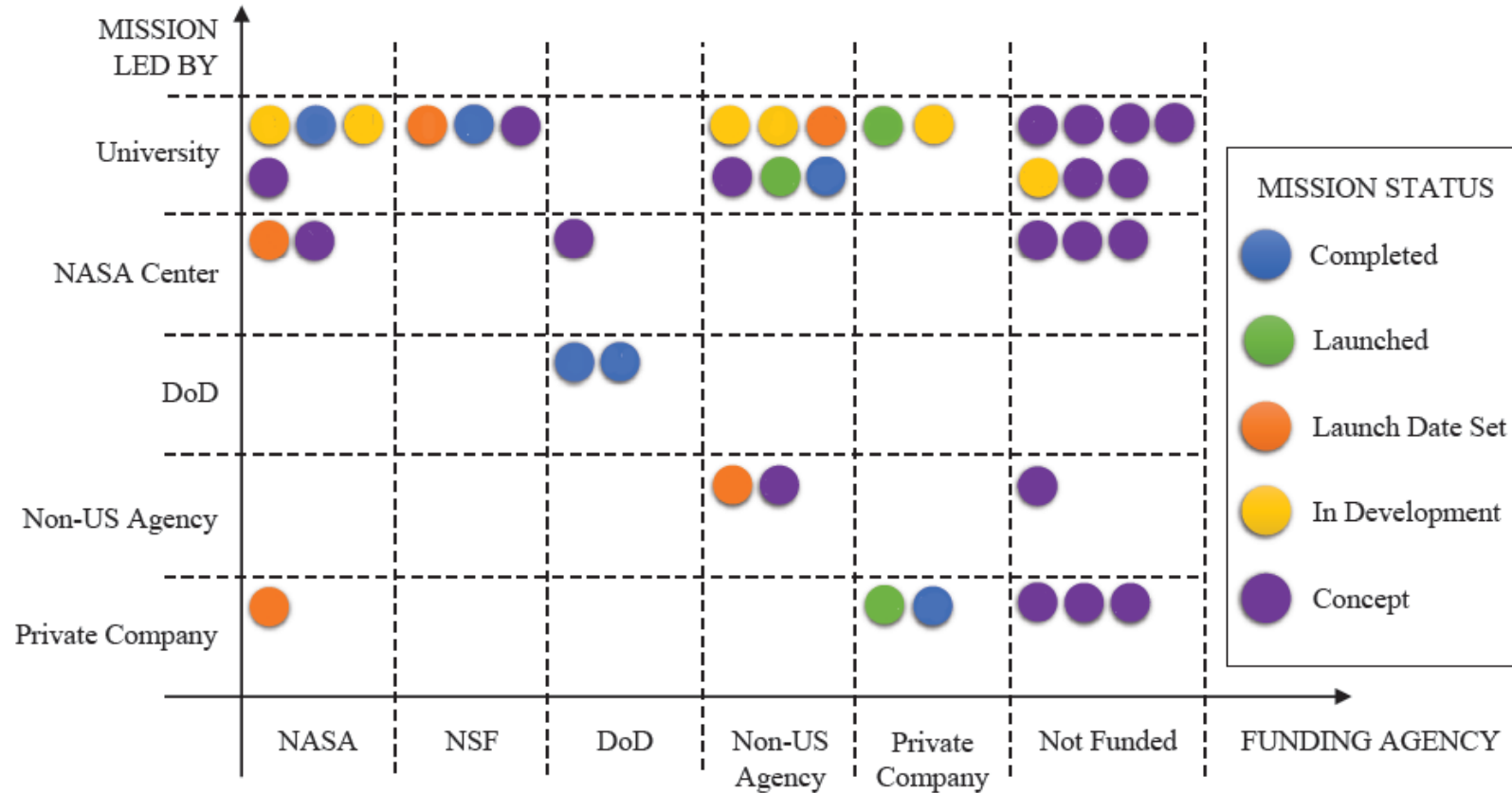
Current and Future Space Missions

- Categorization of thirty-nine multi-satellite missions based on their mission type, formation type and number



1. Bandyopadhyay, S., Foust, R., Subramanian, G. P., Chung, S.-J., & Hadaegh, F. Y. (2016). Review of formation flying and constellation missions using nanosatellites. *Journal of spacecraft and rockets*.
2. Bandyopadhyay, S., Subramanian, G. P., Foust, R., Morgan, D., Chung, S.-J., & Hadaegh, F. (2015). *A review of impending small satellite formation flying missions*. Paper presented at the 53rd AIAA Aerospace Sciences Meeting.

□ Categorization of thirty-nine multi-satellite missions based on their mission status, leading organization and funding source

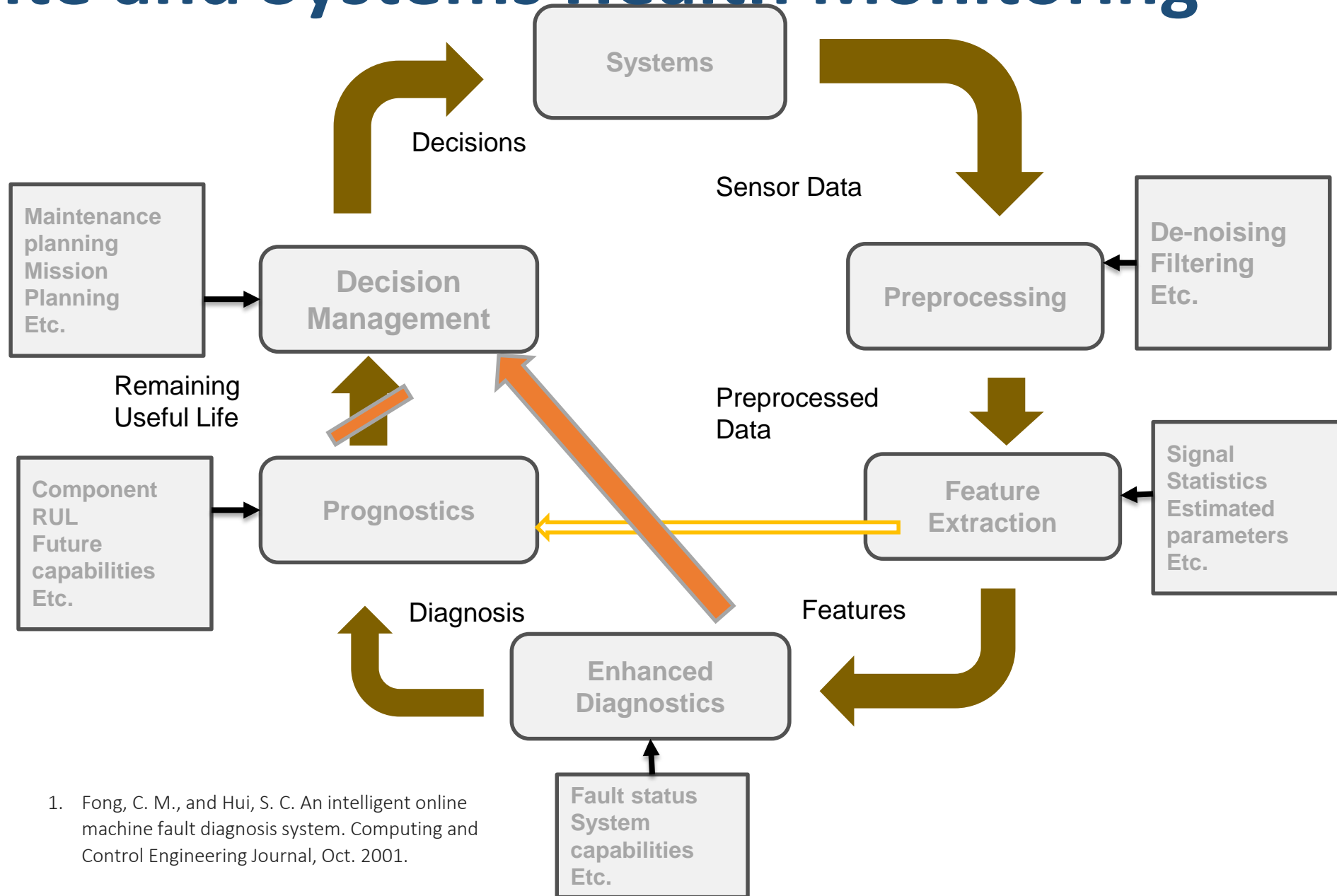


1. Bandyopadhyay, S., Foust, R., Subramanian, G. P., Chung, S.-J., & Hadaegh, F. Y. (2016). Review of formation flying and constellation missions using nanosatellites. *Journal of spacecraft and rockets*.
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Goals for Satellite Missions

- The goal of future space missions is autonomy, with the following requirements identified in the literature
 - Self-requirements
 - self-trajectory
 - self-protection
 - self-scheduling
 - self-reparation
 - Knowledge
 - Awareness
 - Monitoring
 - Adaptability
 - Dynamicity
 - Robustness
 - Resilience
 - Mobility

Satellite and Systems Health Monitoring



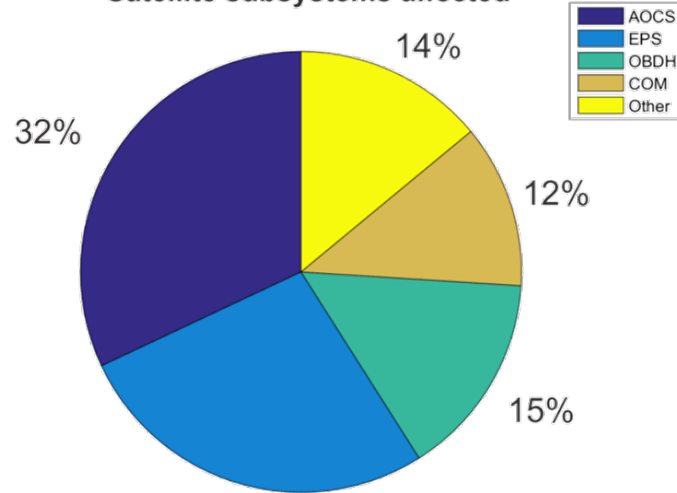
1. Fong, C. M., and Hui, S. C. An intelligent online machine fault diagnosis system. Computing and Control Engineering Journal, Oct. 2001.

Satellite Subsystems

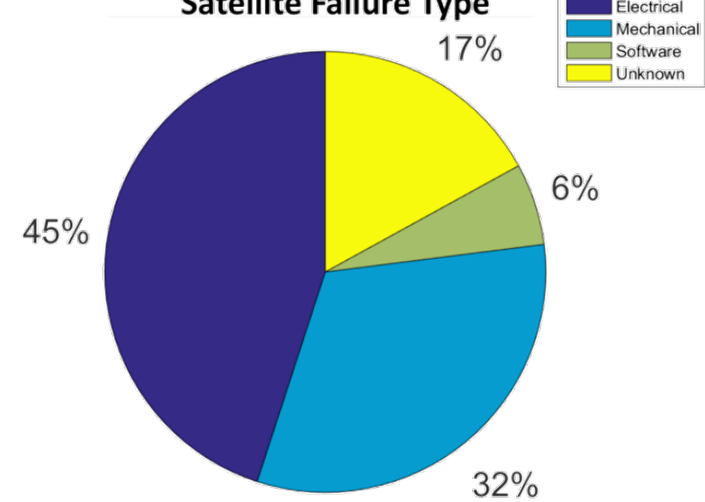
- On-board Data Handling System (OBDH)
- Power System (EPS)
- Communication System - Inter-Satellite Link & Data Downlink and/or Uplink (COM)
- Thermal Control System (TCS)
- Structure (MECH)
- Attitude and Orbit Control System (AOCS)
- Payload (PL)

Satellite Subsystems Anomalies and Failures

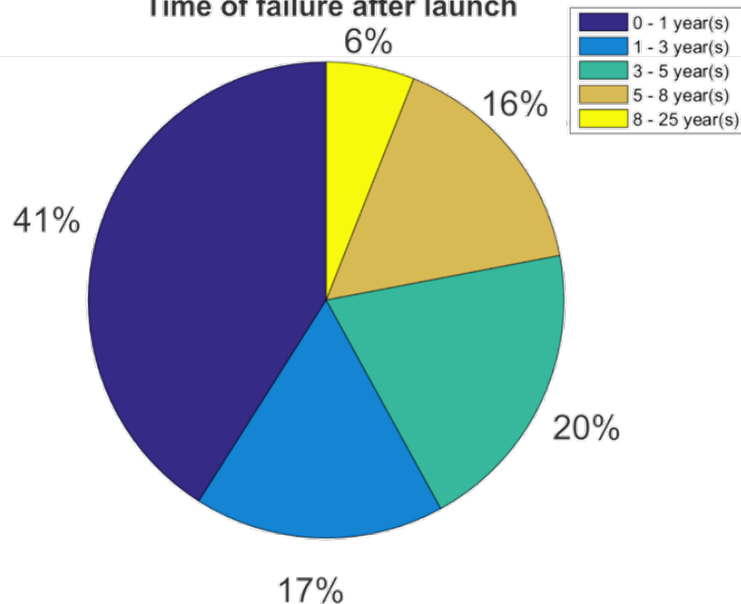
Satellite subsystems affected



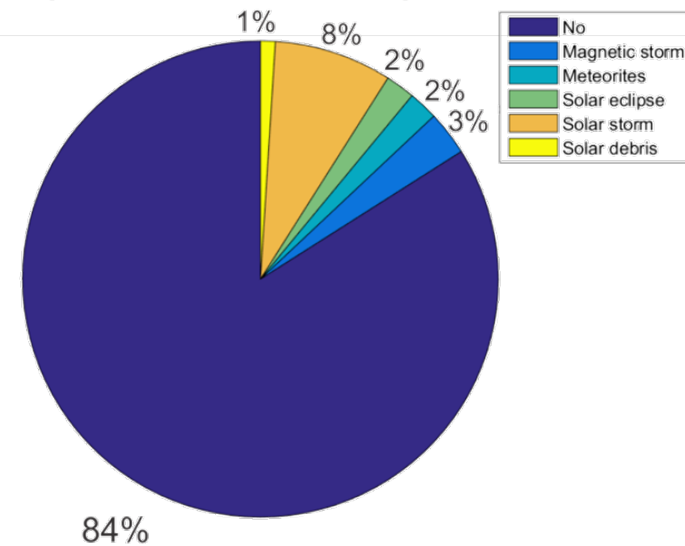
Satellite Failure Type

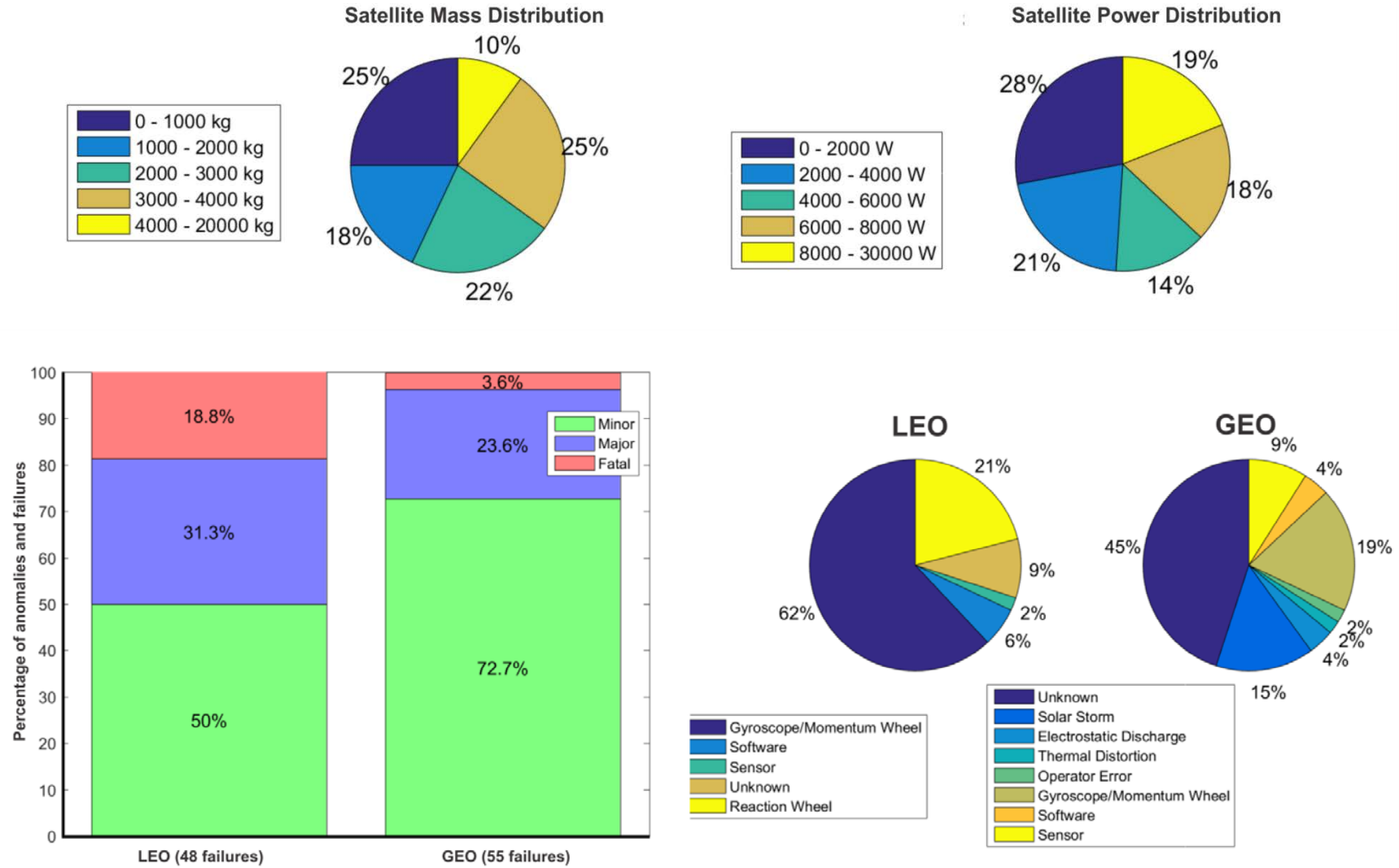


Time of failure after launch

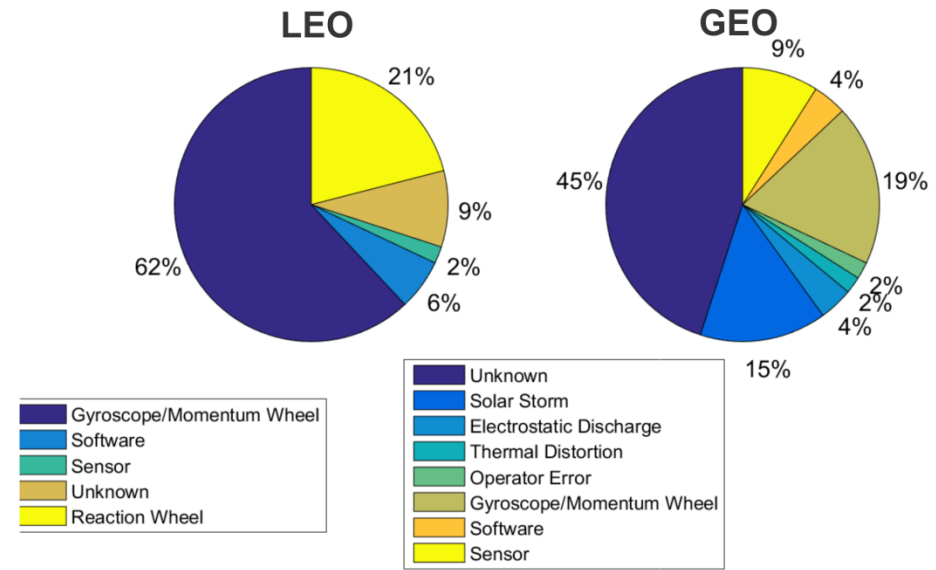
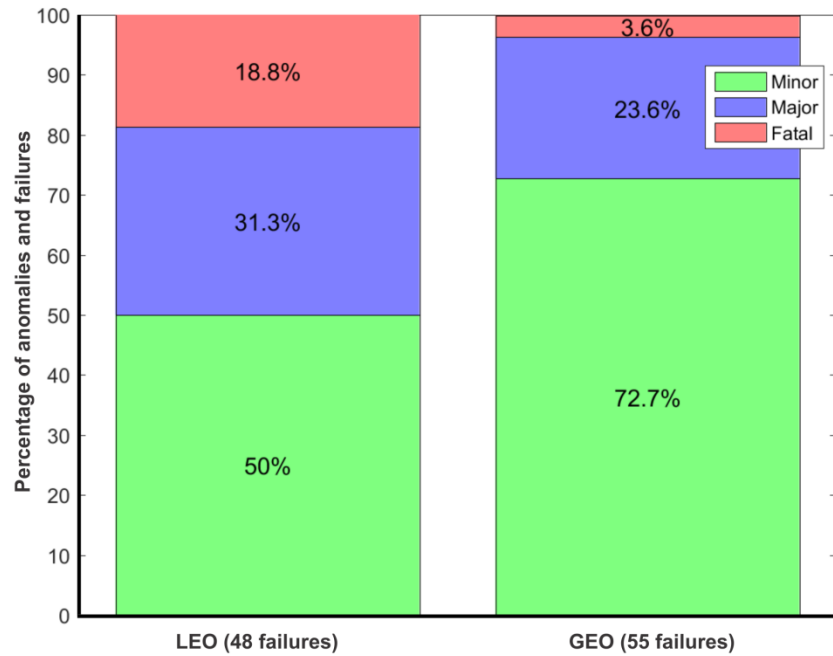


Proportion of failure due to space environment

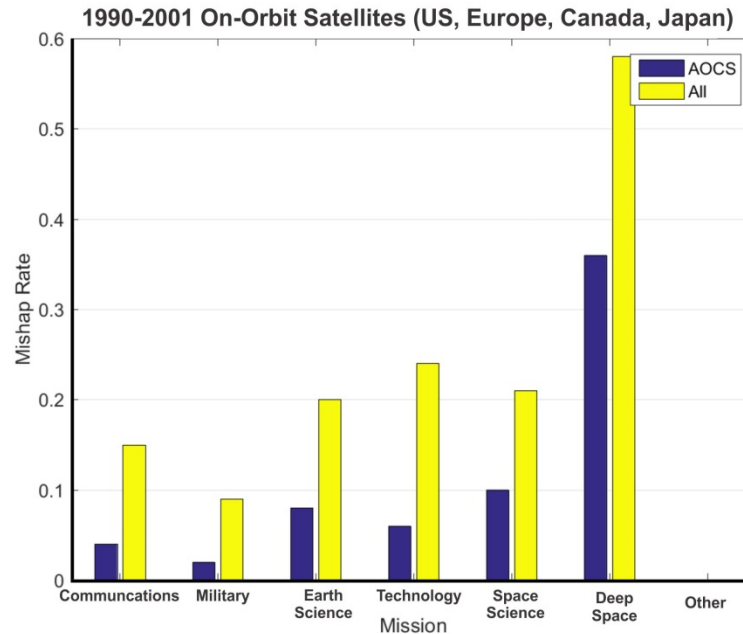
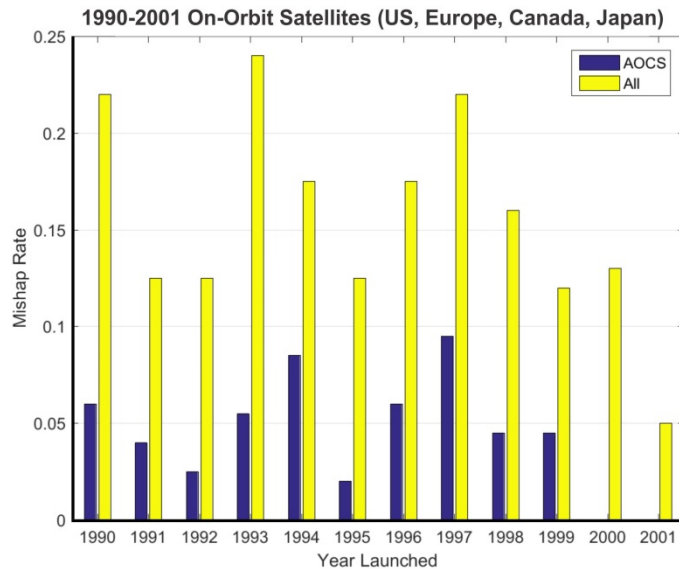
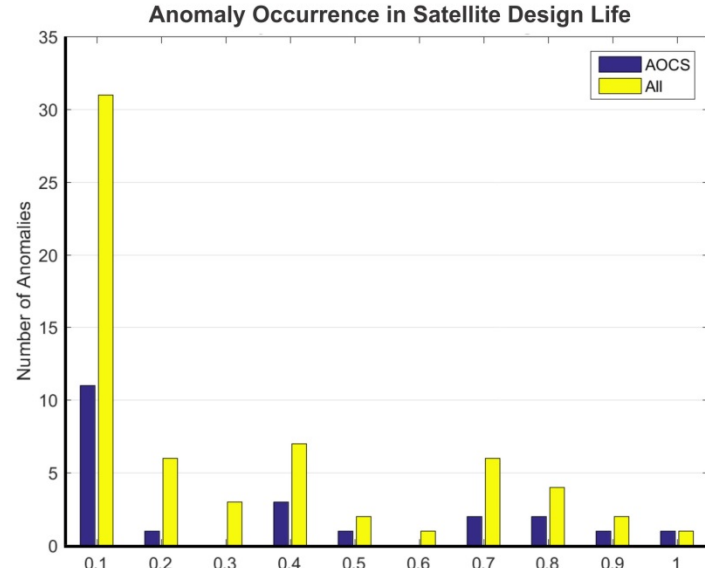
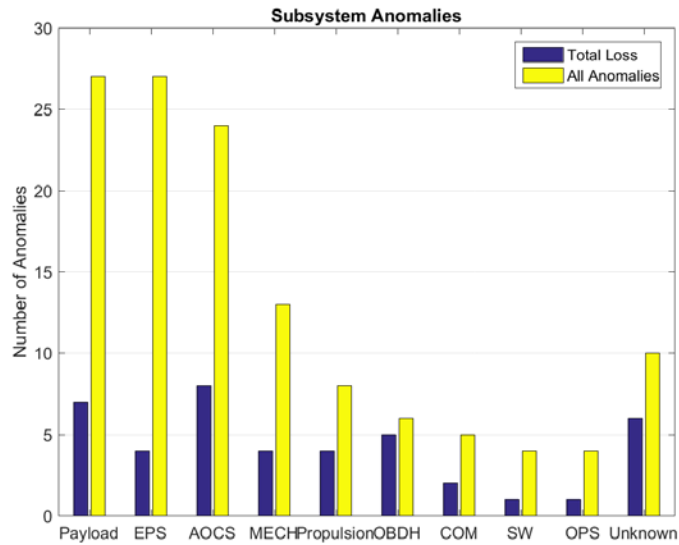




1. Wayer, J. K., Castet, J. F., & Saleh, J. H. (2013). Spacecraft attitude control subsystem: Reliability, multi-state analyses, and comparative failure behavior in LEO and GEO. *Acta Astronautica*, 85, 83-92.



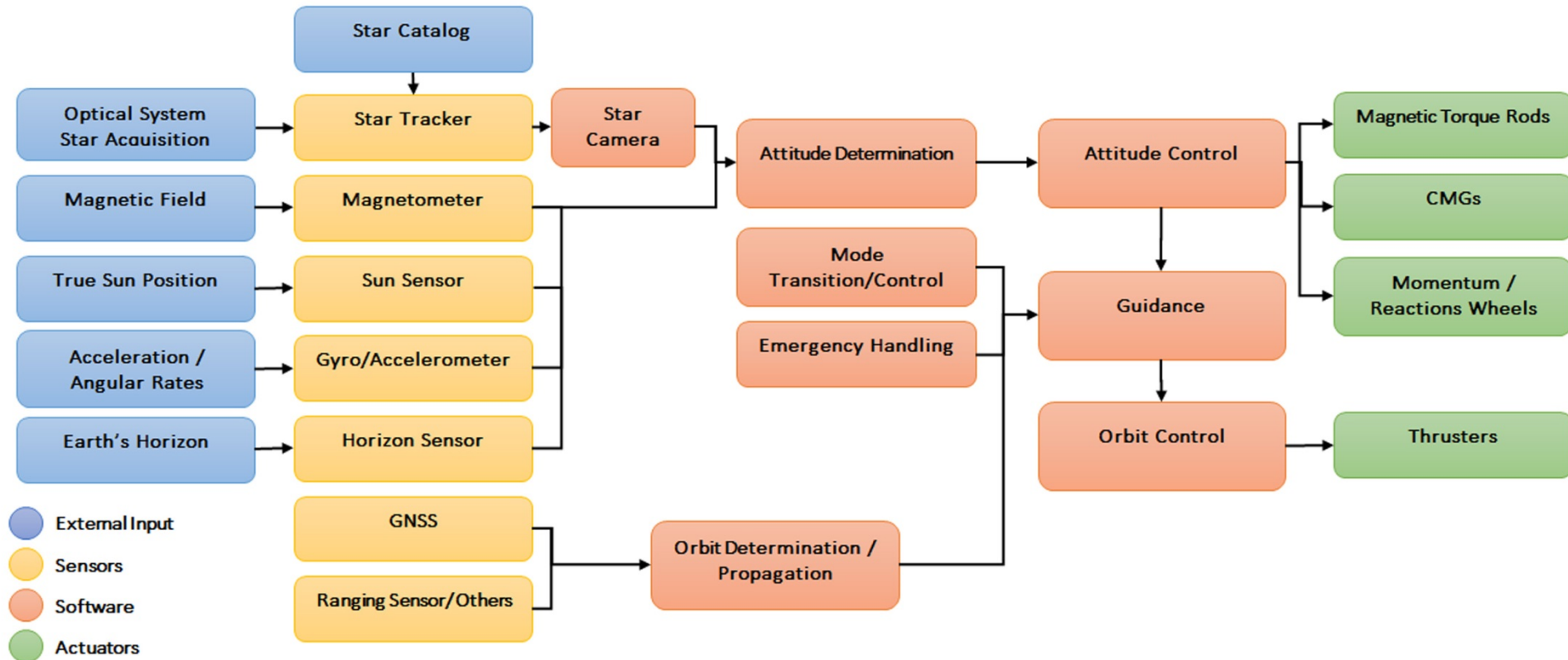
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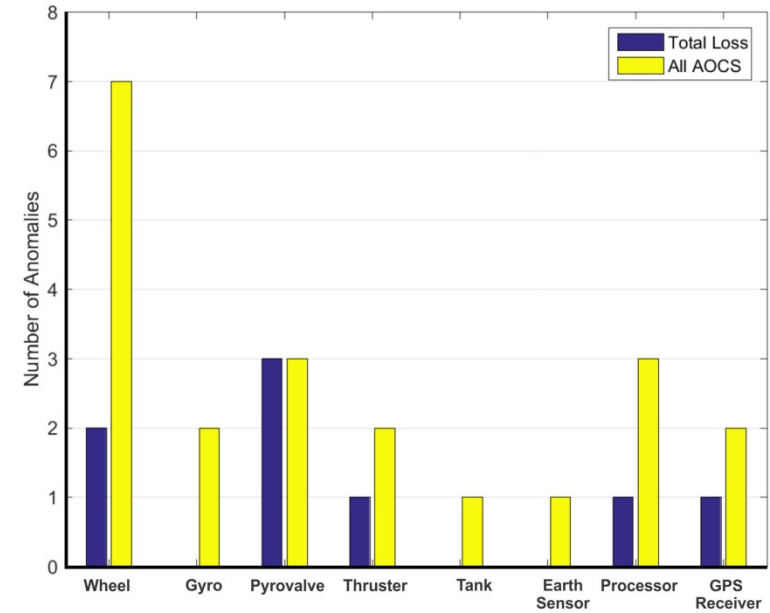
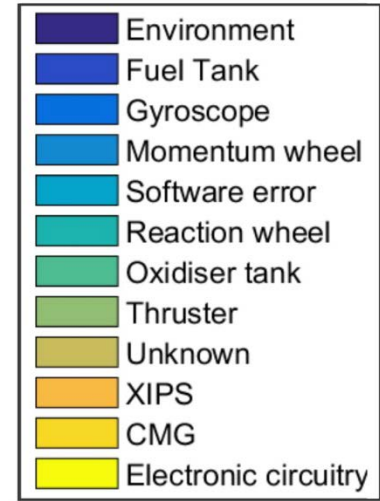
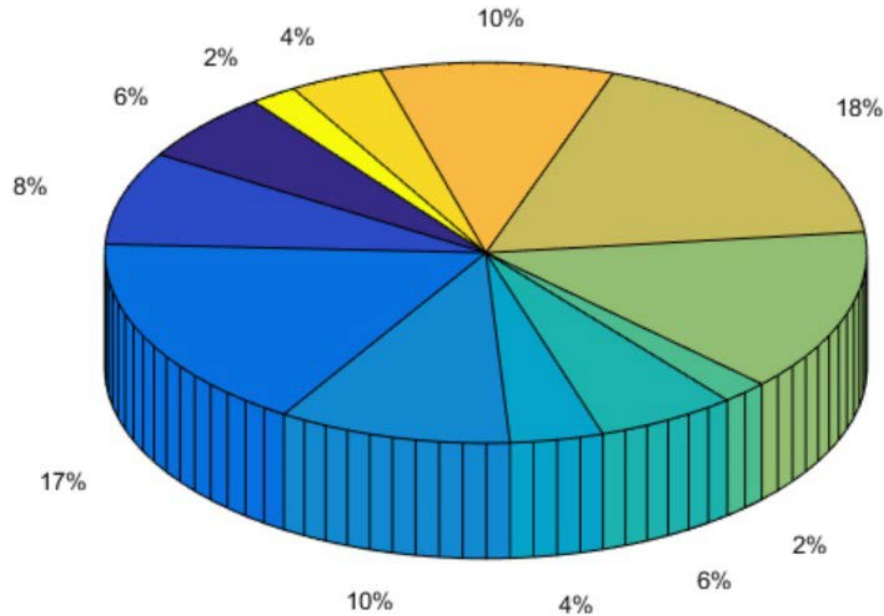
1. Robertson, B., & Stoneking, E. (2003). Satellite GN & C anomaly trends. *Advances in the Astronautical Sciences*, 113, 531-542.

SHM for AOCS Subsystem

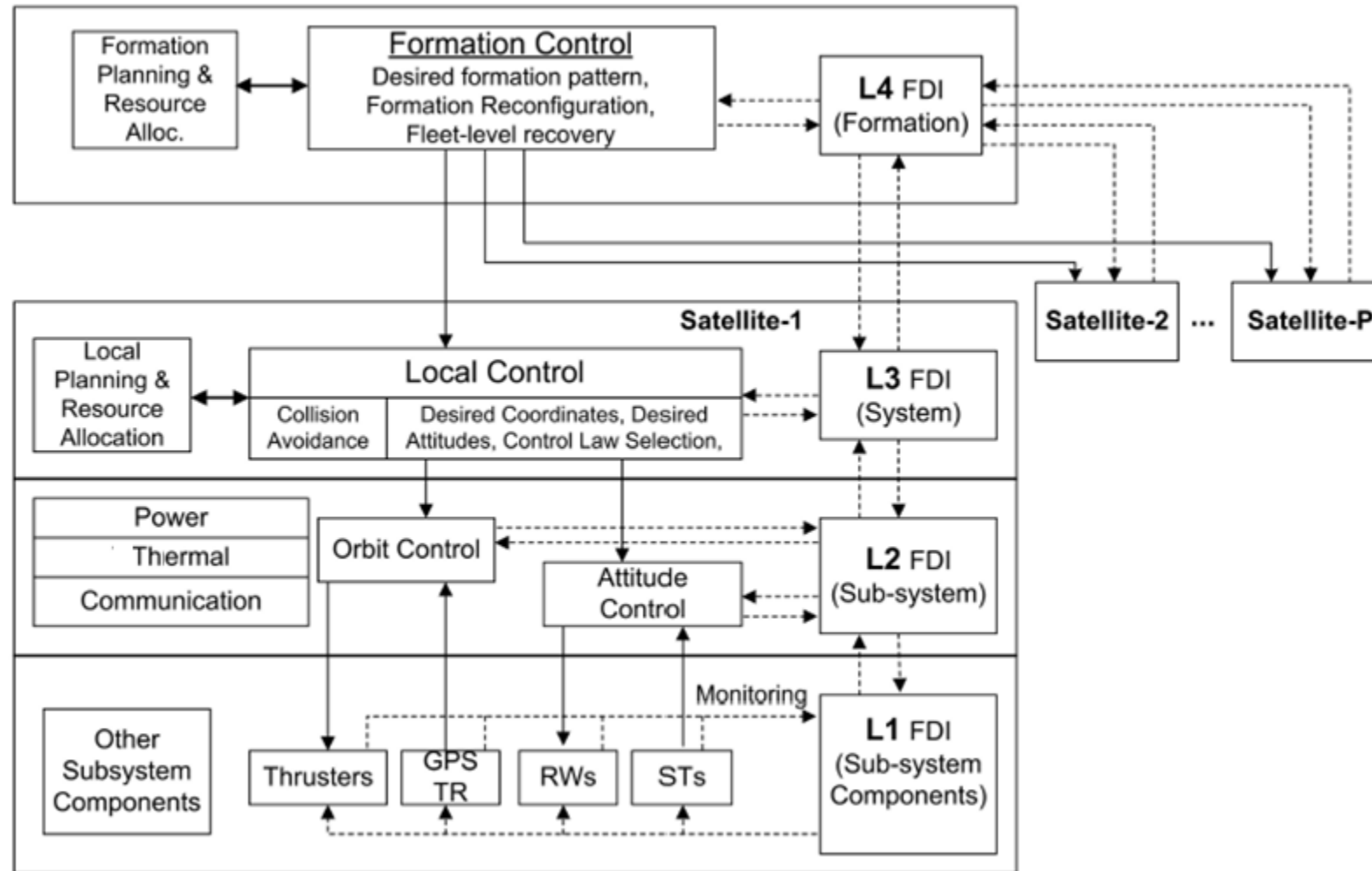
Attitude and Orbit Control



Component Failure



1. Tafazoli, M. (2009). A study of on-orbit spacecraft failures. *Acta Astronautica*, 61(1-3), 1-10.
2. Robertson, B., & Stoneking, E. (2003). Satellite GN & C anomaly trends. *Advances in the Astronautical Sciences*, 113, 531-542.

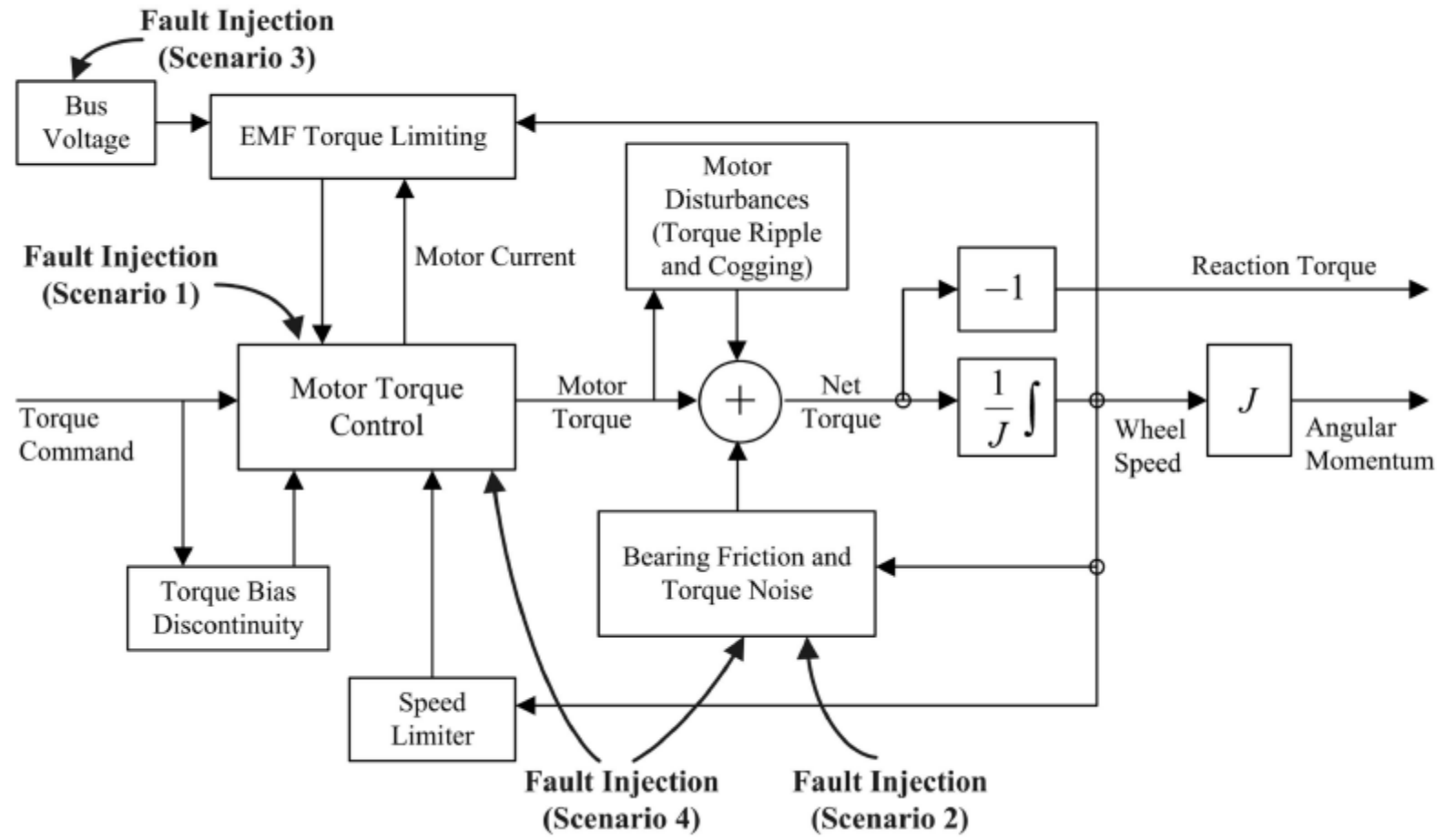


Proposed FDI framework for a multi-platform formation flight space missions.

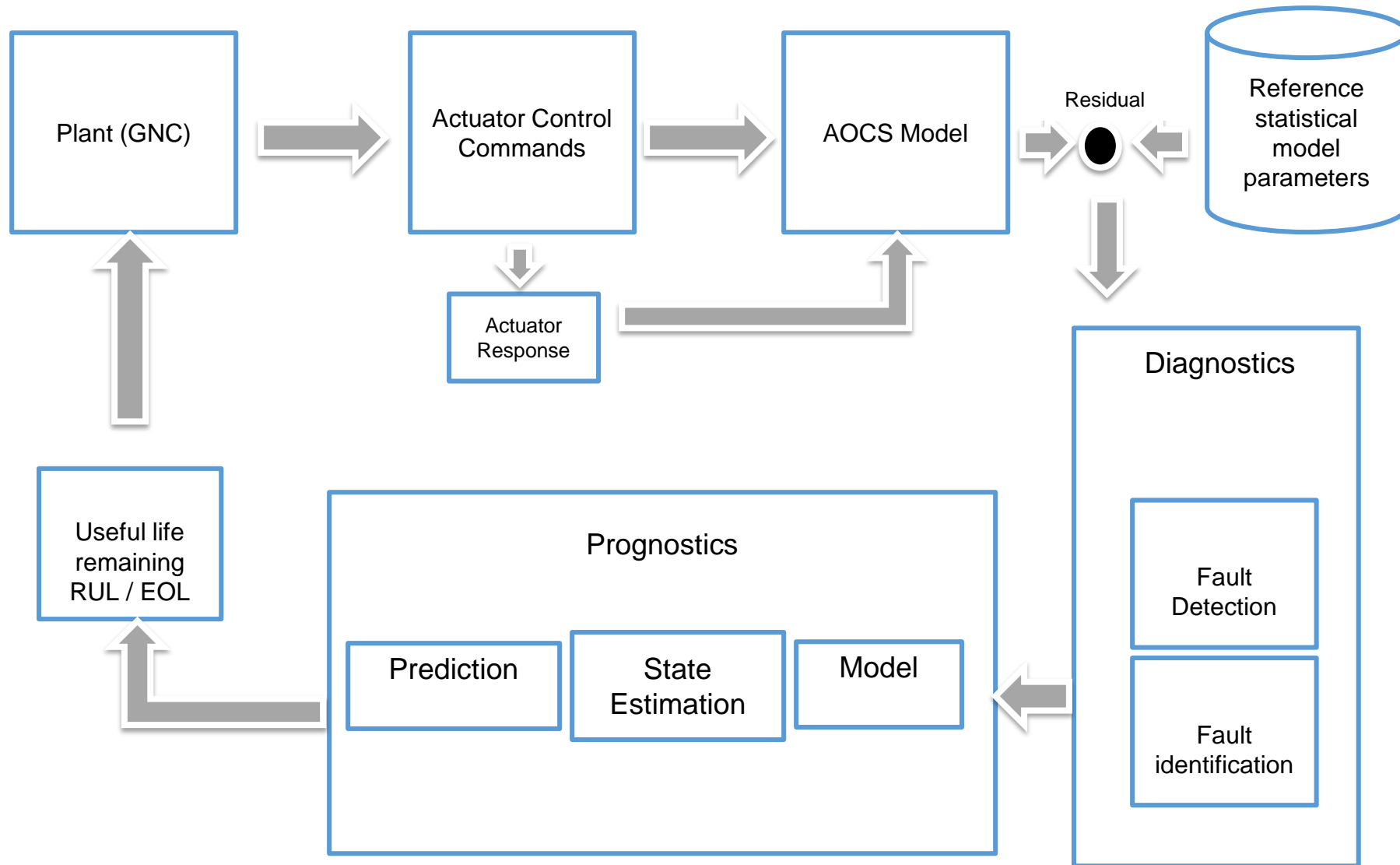
1. Barua, A., & Khorasani, K. (2011). Hierarchical fault diagnosis and health monitoring in satellites formation flight. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 41(2), 223-239.

PHM Frame work for AOCS

- Model based prognostics algorithms to predict the remaining useful life of AOCS components using a probabilistic approach incorporating the uncertainty model for each component to estimate the RUL of the complete AOCS system for the satellite.
- This information will be useful for the formation to maintain their position or to reconfigure within the estimated time for uninterrupted mission deliverables



Health Management Approach



Conclusion

- SHM for small satellites is important for autonomy
- AOCS contributes to about 32% of all on-board failures
- AOCS is a critical component in satellite formation flying
- Telemetry data for deep space missions of small satellite is unavailable
- 84% of all AOCS anomalies and failures are from related to design and operations
- ISHM will provide useful information to designers for more robust design

Background

- Based on NASA's decadal survey, there is a clear need to prioritize the development of satellite swarm technology for studies of space physics and Earth science.
- In order to make deep space missions gain autonomy, the sources of mission decay and failure must be known.
- A survey found that the Attitude and Orbit Control Subsystem (AOCS) had a high incidence of failure
- This makes the AOCS a great candidate for systems health management

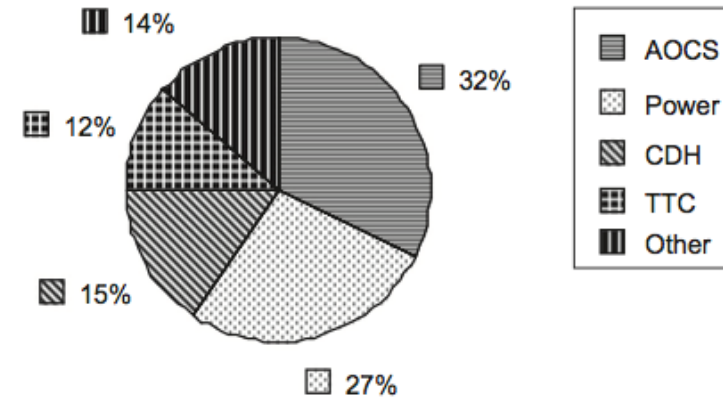


Fig. 1. Spacecraft subsystems affected.

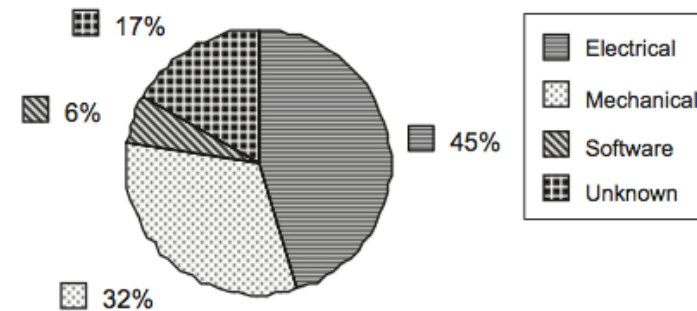


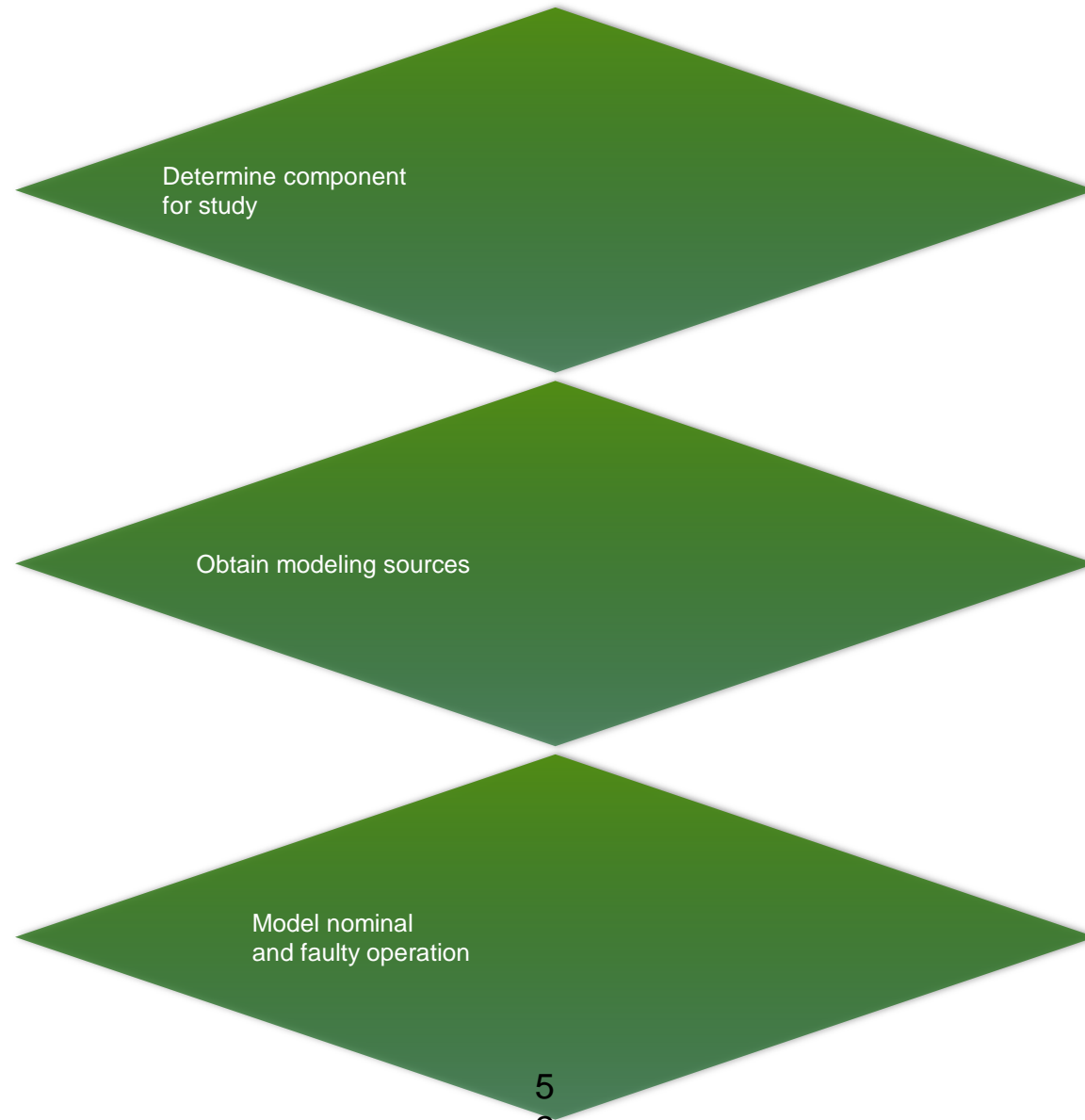
Fig. 2. Spacecraft failure type.

Tafazoli, M. (2009). A study of on-orbit spacecraft failures. *Acta Astronautica*, 64(2-3), 195-205. doi:10.1016/j.actaastro.2008.07.019

What is the AOCS?

- ❑ This stands for Attitude and Orbit Control System, but it may also be called Attitude Determination System (ADS) or Attitude Determination and Control Subsystem (ADCS).
- ❑ This is the subsystem that stabilizes the spacecraft and orients it in desired directions during its operation.

Scope



Component Determination

Actuators

- Magnetorquers
- Reaction Wheels
- Momentum Wheels
- Control Momentum Gyros (CMGs)
- Thrusters

Component

Determination

- Relevance: is it suitable for future satellite missions?
- History: does the component have records of failure?
- Benefits: what are the pros of using this actuator?

Component Determination

Actuators

Magnetorquers

Reaction Wheels

Momentum Wheels

Control Momentum Gyros (CMGs)

Thrusters

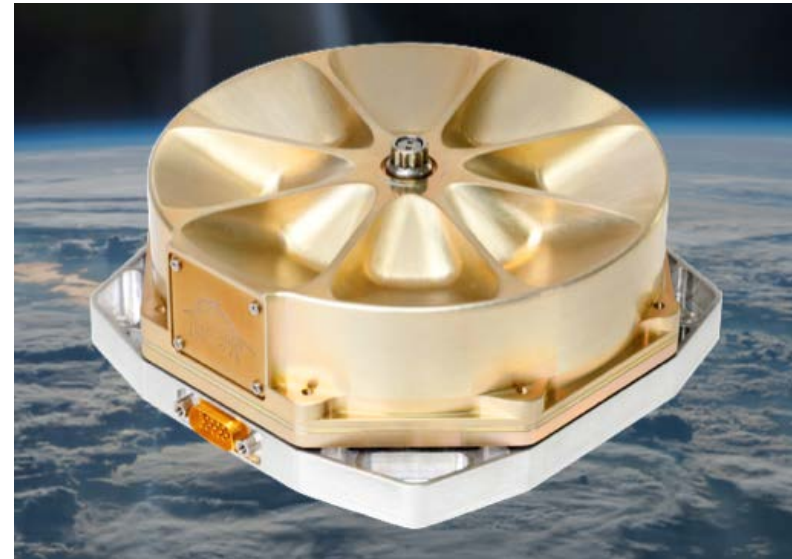
Pointing accuracy

Low energy consumption

Known cause of mission decay and failure

Reaction Wheels

- ❑ The Reaction Wheel Assembly (RWA) is an actuator which in essence consists of a flywheel attached to a brushless DC motor.
- ❑ They produce a torque that is applied to the spacecraft to correct its position.



Source: Blue Canyon Technologies

- ❑ A minimum of three reaction wheels, one per body axis, is required to maintain attitude
- ❑ Reaction wheels are used for zero-momentum control or momentum-bias control on ADCS, which are the two forms of three-axis control



Source: Blue Canyon Technologies

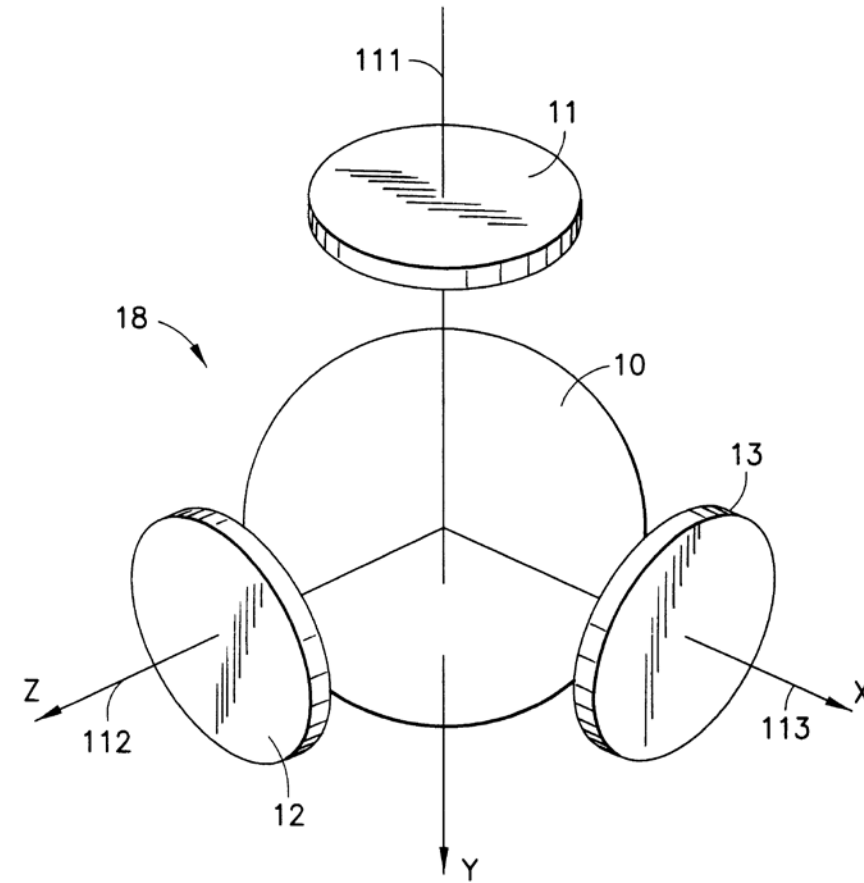


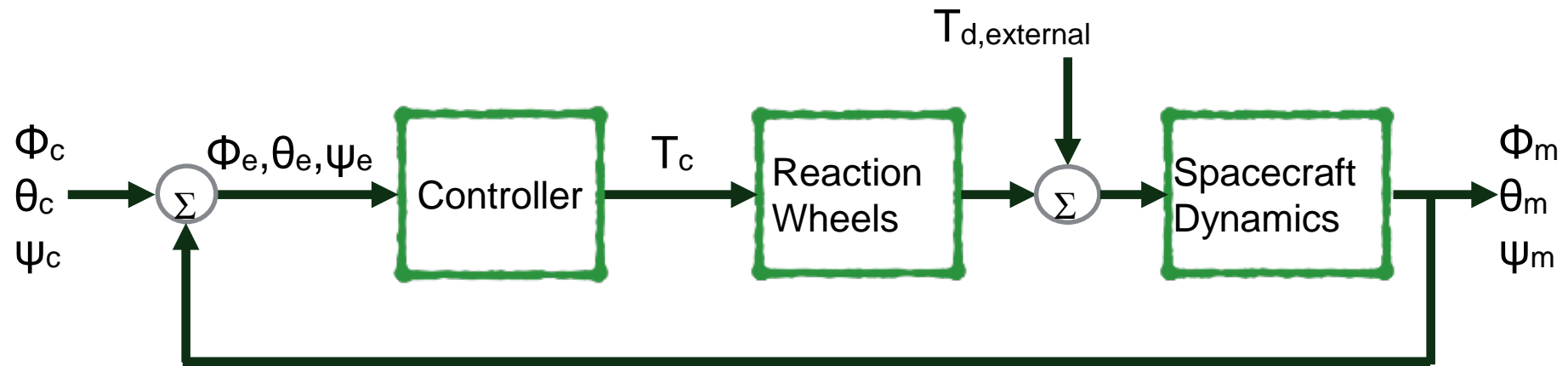
FIG.3

From US patent: *Onboard attitude control using reaction wheels*

Obtain modeling

- ## sources
- What needed to be determined?
 - Parameters
 - Model
 - Faults

SCHEMATIC OF an AOCS Actuated by RWA



Equations

□ Mechanical:

$$T_m - T_f + T_d = J\omega$$

□ Electrical:

$$V_R = V_S - V_{emf}$$

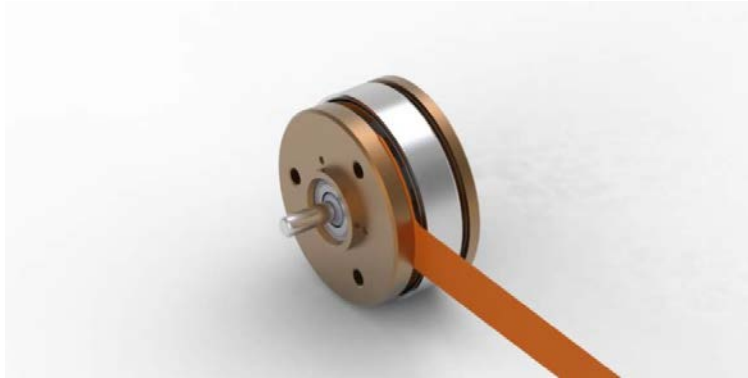
$$V_R = k_f(i_c - i_m) - k_{emf}\omega$$

Resistance Voltage

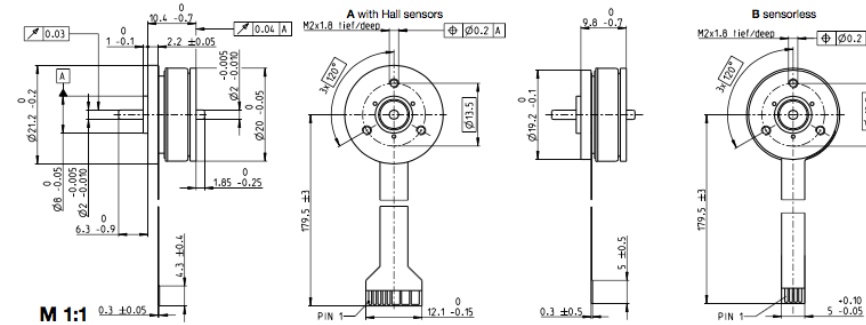


Commanded Voltage

Back EMF Voltage



EC 20 flat Ø20 mm, brushless, 3 Watt



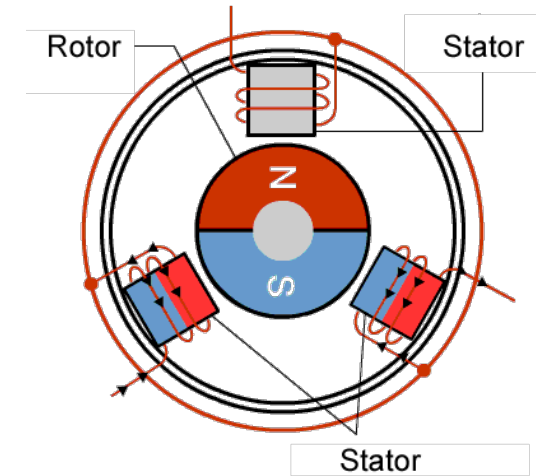
maxon flat motor

Source: Maxon Motor

Parameter	Notation	Value
Torque constant	k_m	5.88 mNm/A
Back EMF constant	k_{emf}	5.89 mNm/A
Inertia of rotor	J	1.12×10^{-6} kg-m ²
Resistance	R	6.67 Ω
Number of poles	N	8
Viscous friction coefficient	b	5.1965×10^{-7} Nms
Static Imbalance	s	1.2 g-mm
Dynamic Imbalance	d	20 g-mm ²
Gain	k	220 V/A*s

Motor disturbances

□ **Torque Ripple:** result of the drive torque being a superposition of rectified sine waves. The torque ripple of a motor with a greater number of poles is at a higher frequency, where it is less problematic.



□ **Cogging torque:** is a result of the magnets in the rotor moving past a ferromagnetic

□ **Cogging torque (f_1):** where C is the amplitude of the cogging torque, N is the number of poles, and ω is the angular speed

$$f_1(\omega) = C \sin\left(\frac{Nt}{2}\omega\right)$$

□ **Torque Ripple** $f_2(\omega) = B \sin(3Nt\omega)$ e cogging torque, N
is the number of

Flywheel Imbalances

❑ **Static imbalance:** condition that the wheel's center of mass is not on the axis of rotation.

❑ **Dynan** $F_c = ma_c = m \frac{v^2}{r} = mr\Omega^2$, the axis of rotation of the wheel is not on the principal axis.

$$\tau = mrd\Omega^2.$$

Simulation Scenarios

□ Using three different inputs, the following scenarios were simulated:

1. Nominal operation

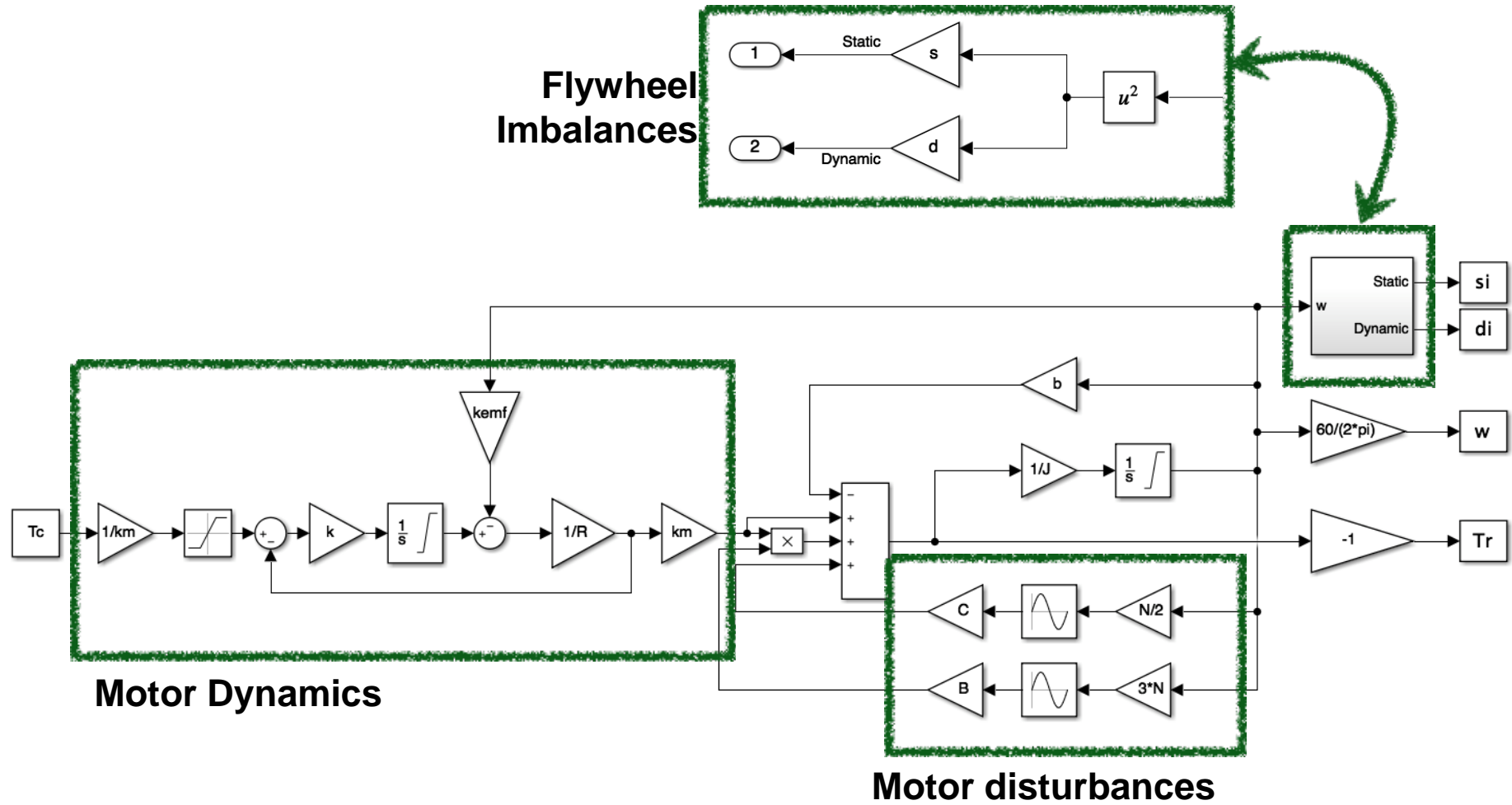
2. Loss of effectiveness of motor torque:

$$k_m^{f1} = 0.7k_m^n$$

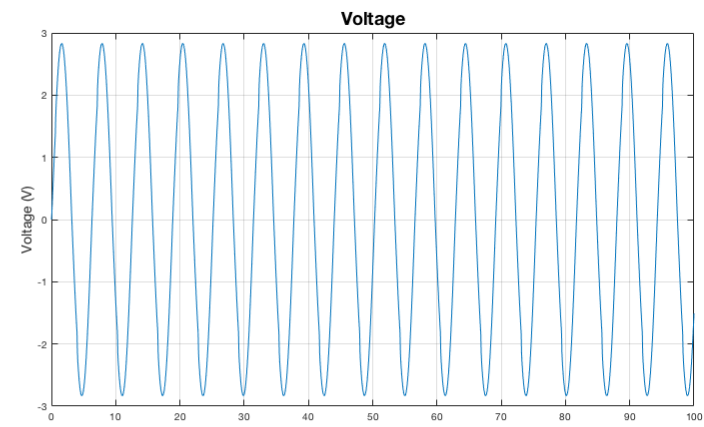
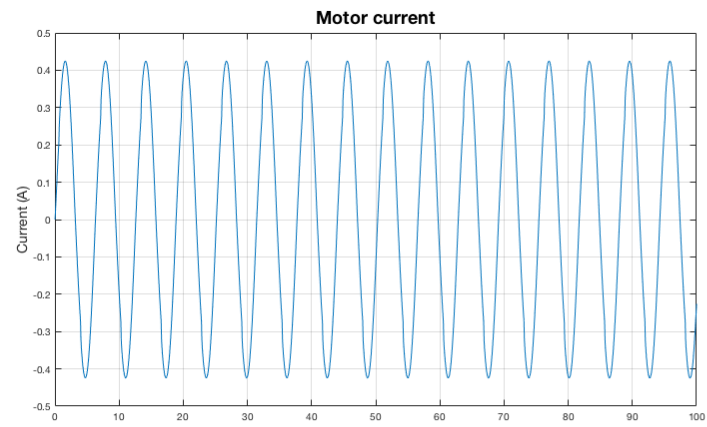
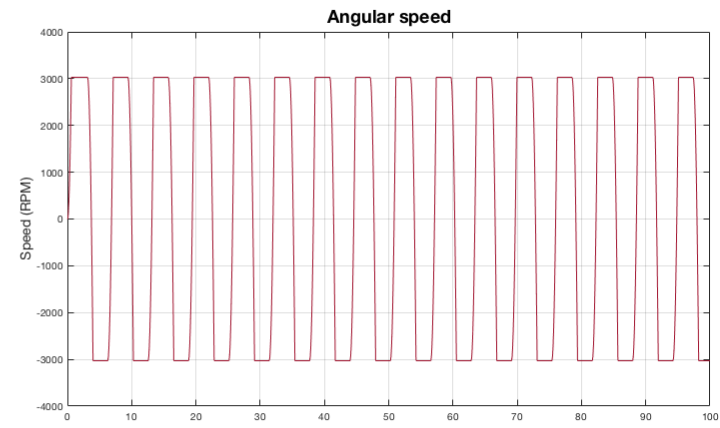
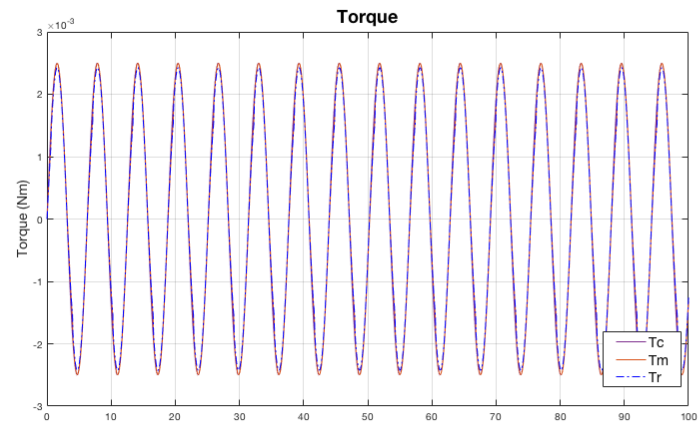
3. Voltage disturbance: $V_f = 1.5 * \sin(30 * t)$

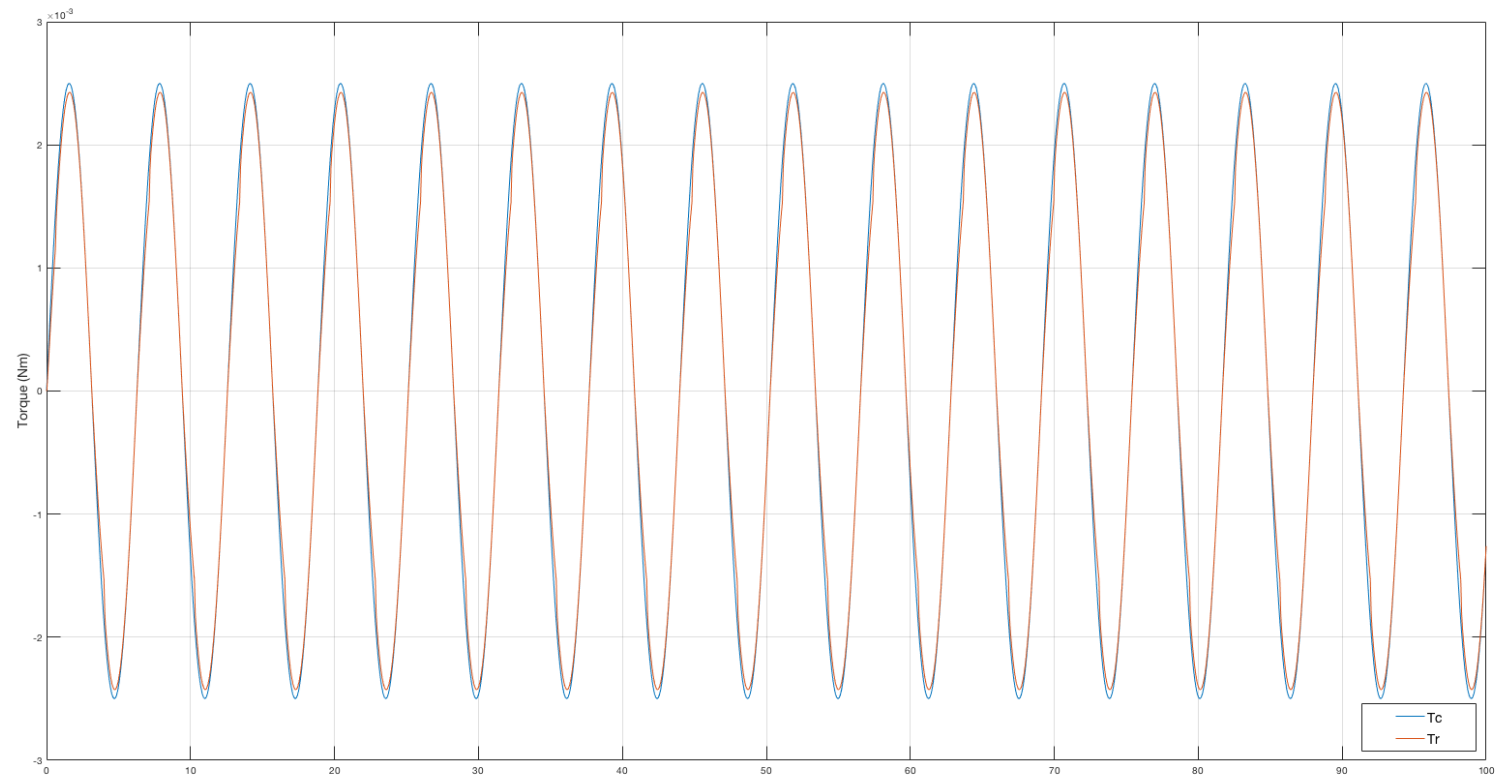
4. Change in friction: including Coulomb friction,
 $c = 0.00103$

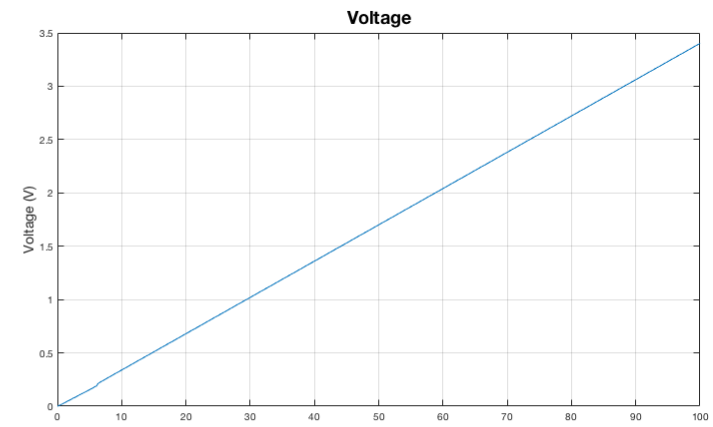
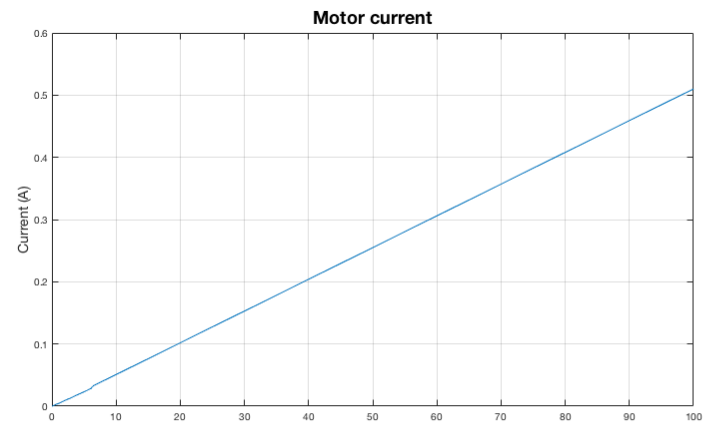
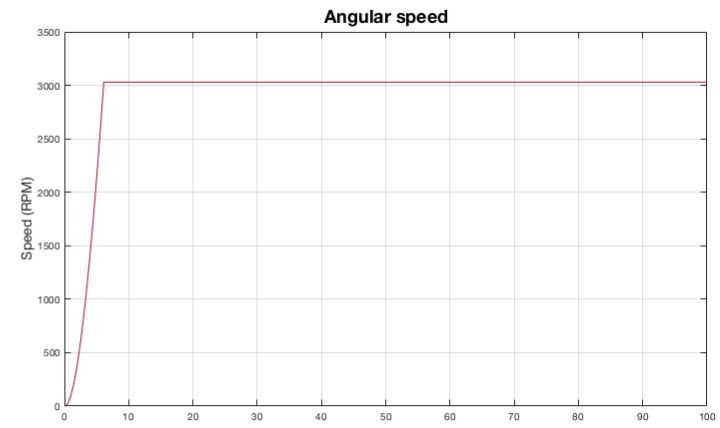
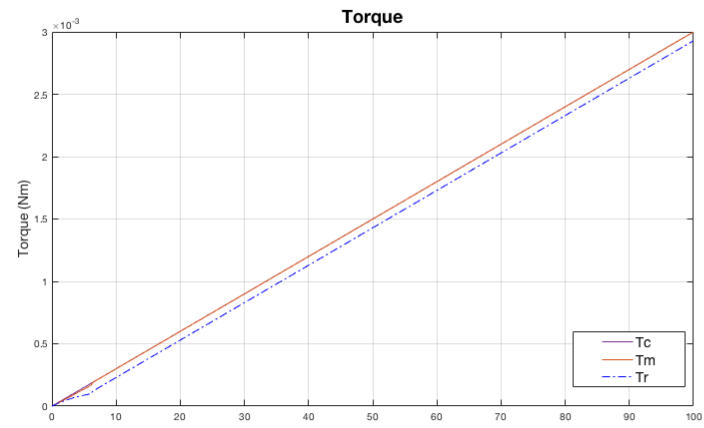
Simulink Model

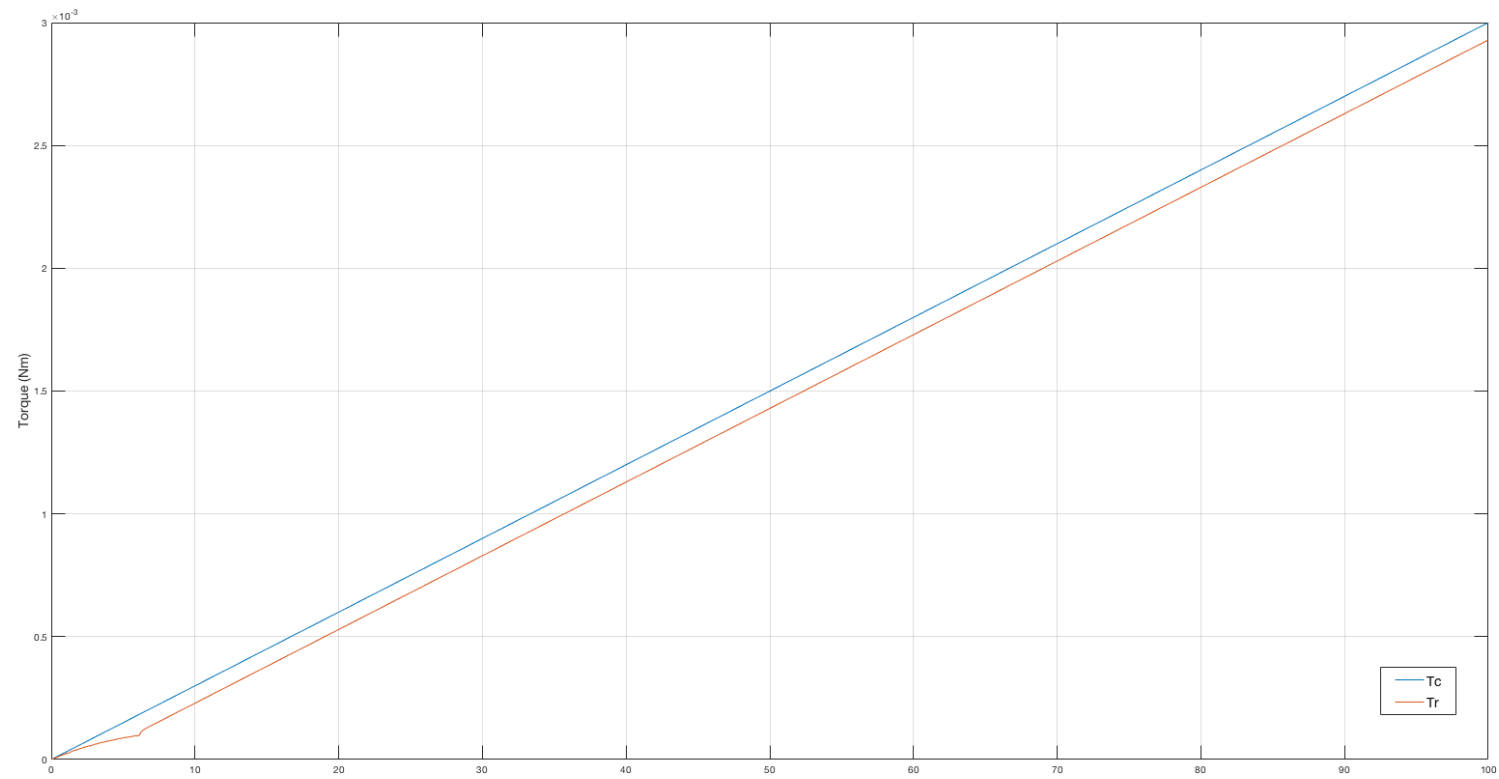


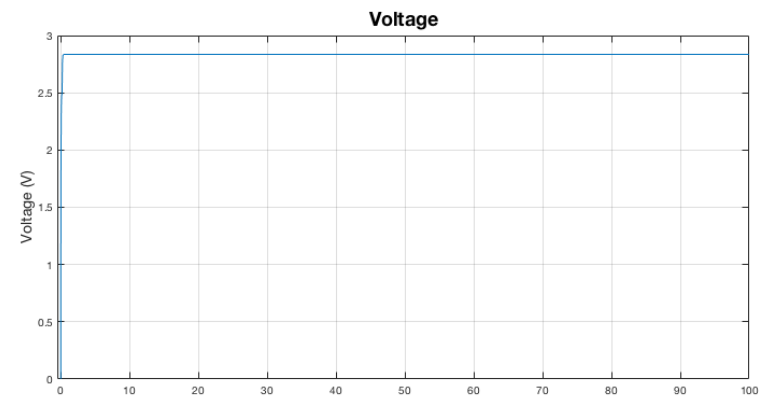
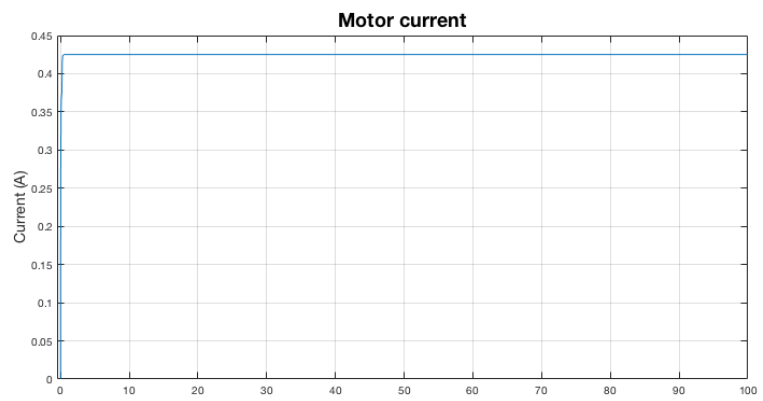
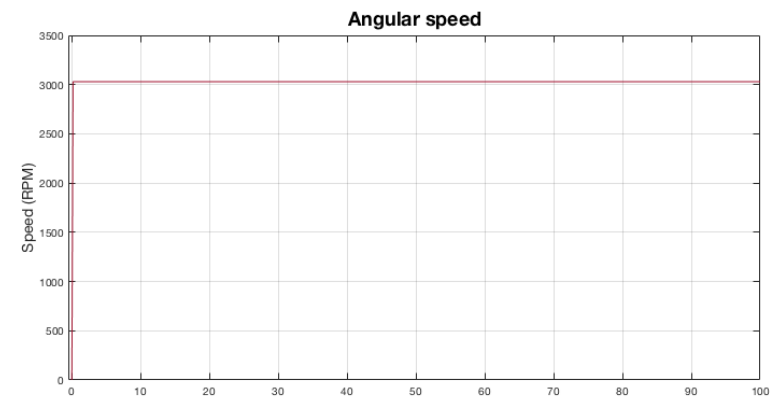
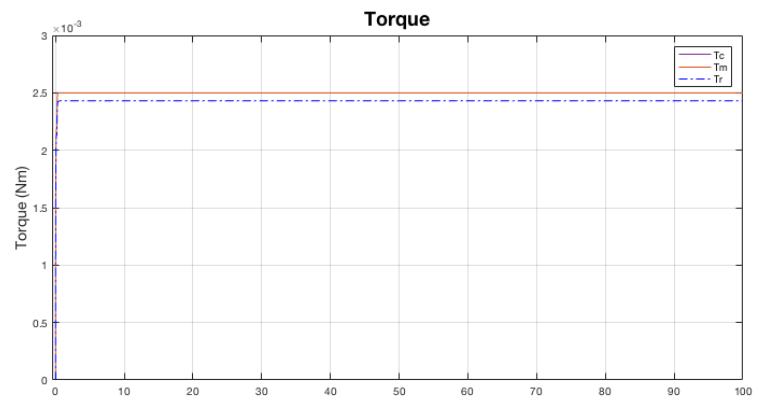
Nominal Operation

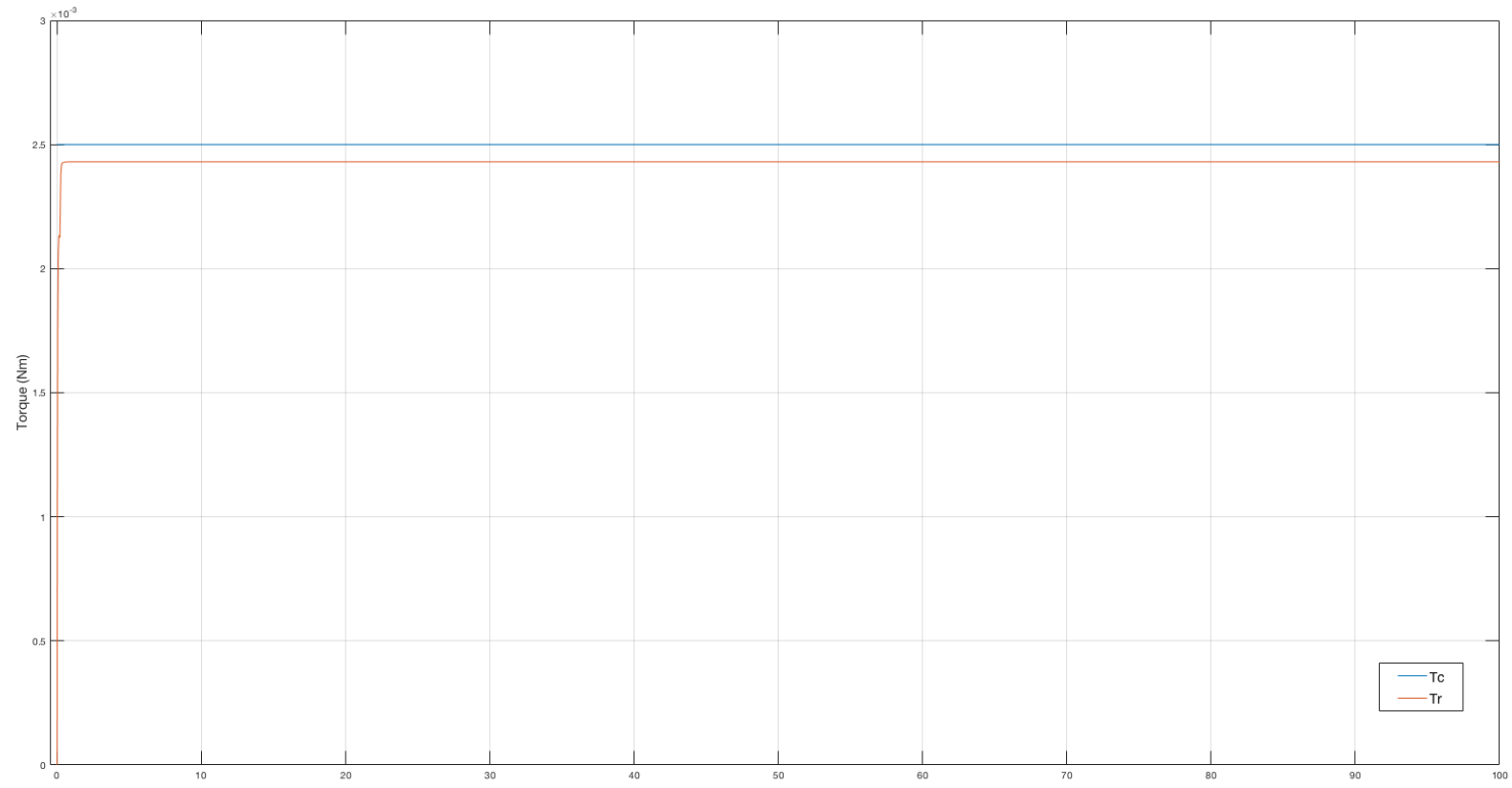




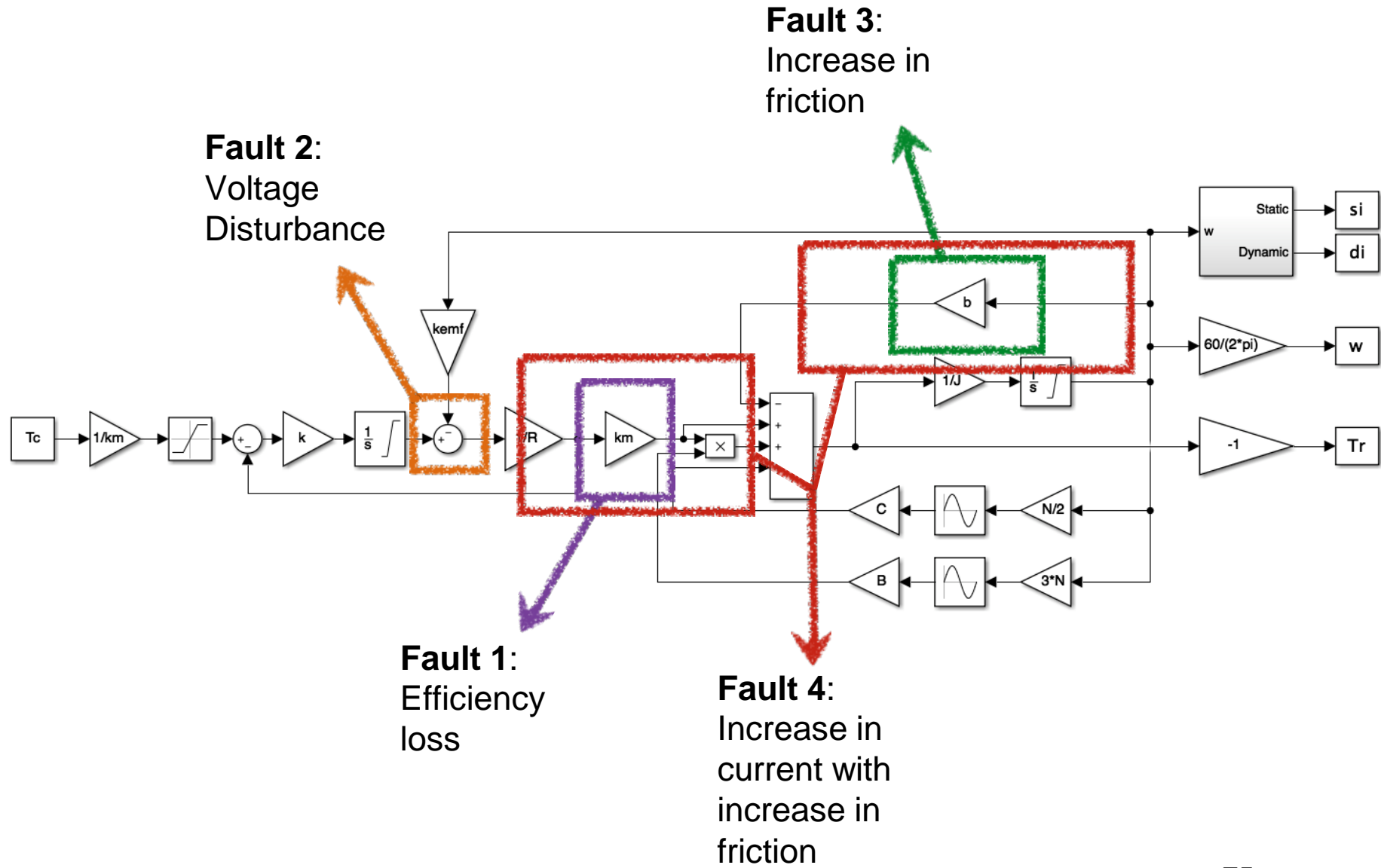




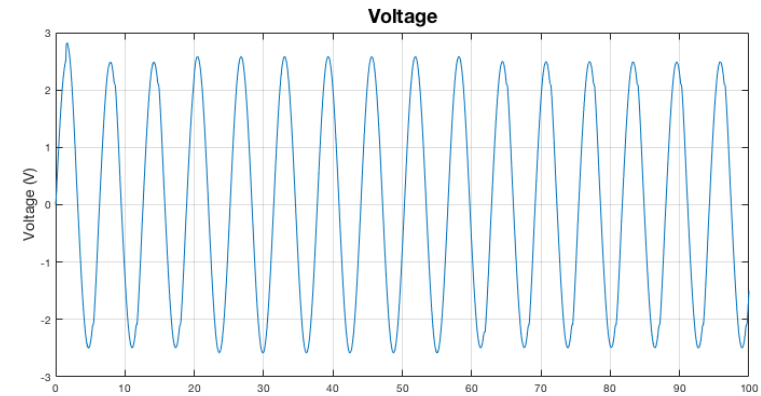
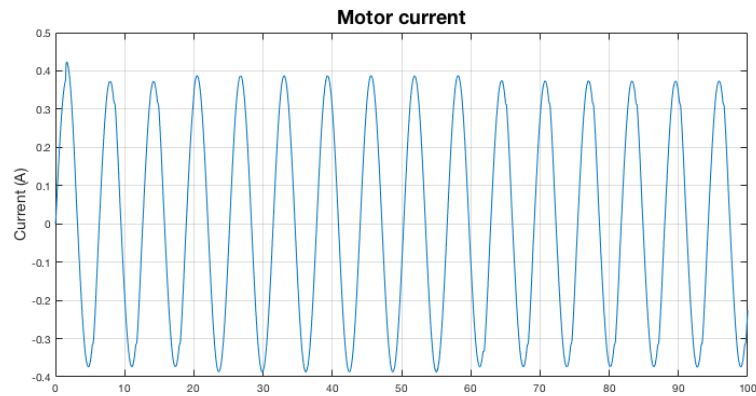
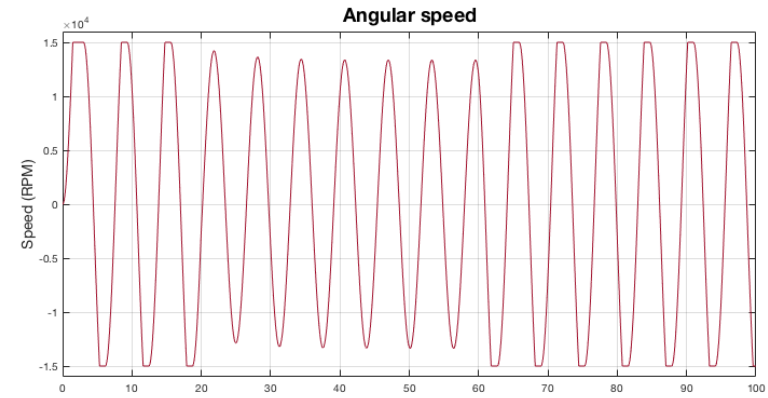
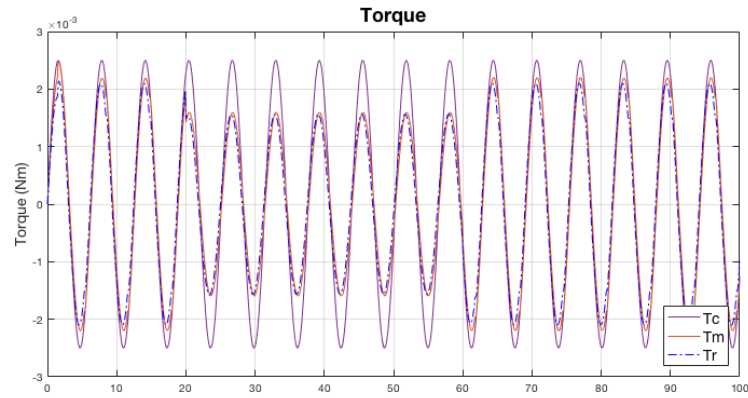


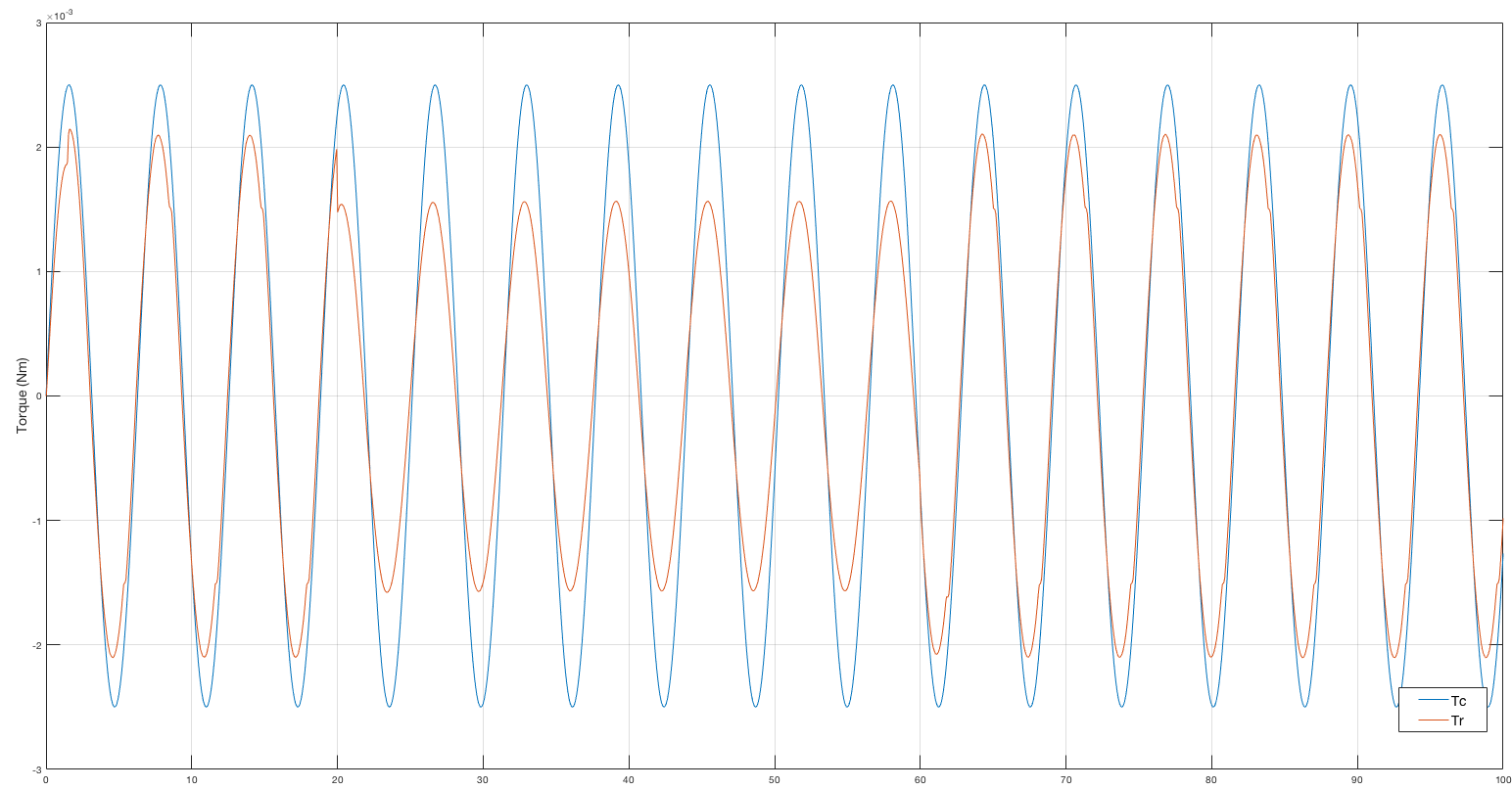


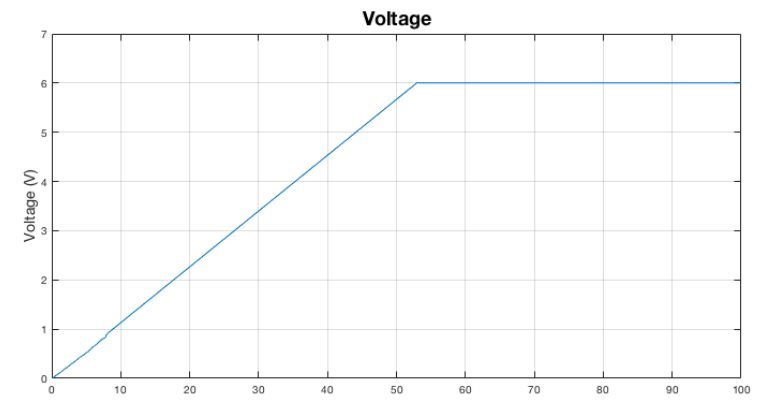
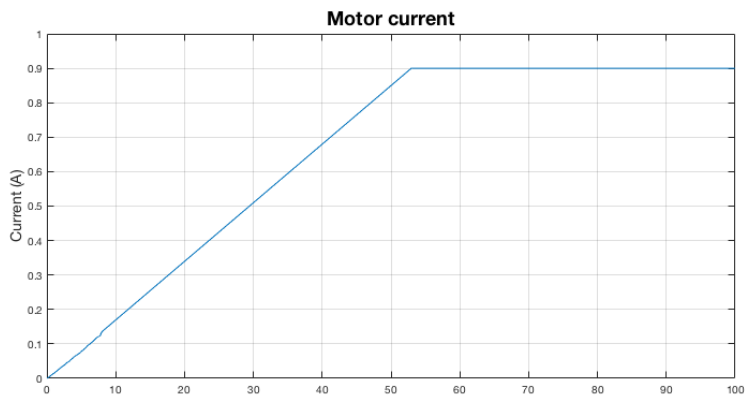
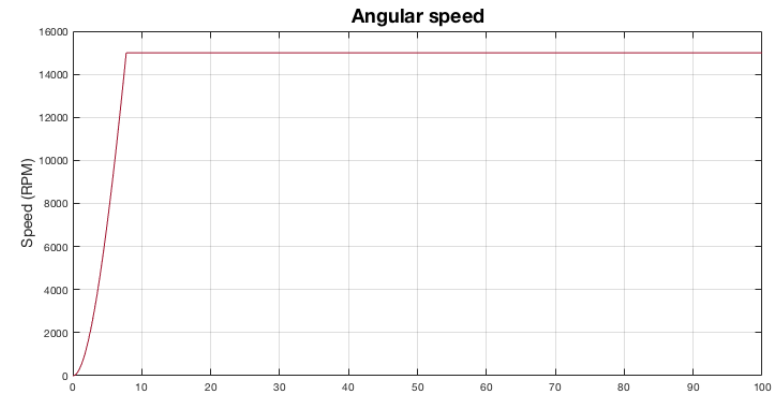
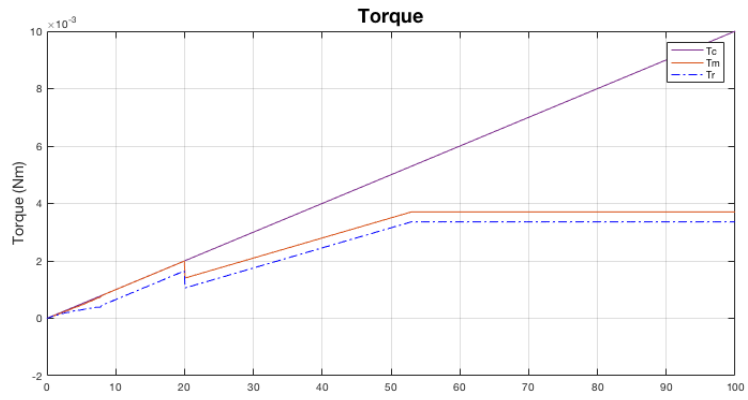
Faulty Operation

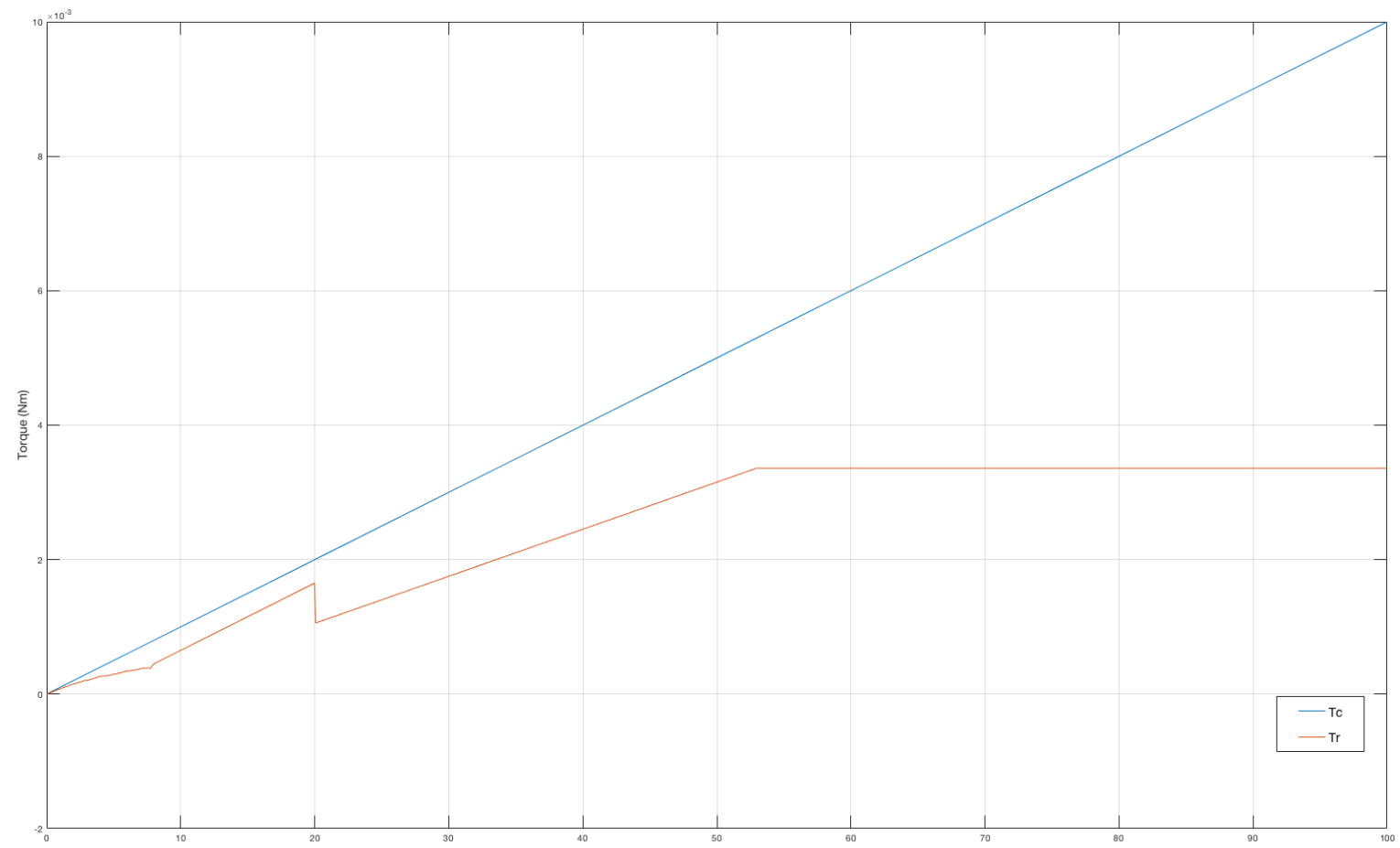


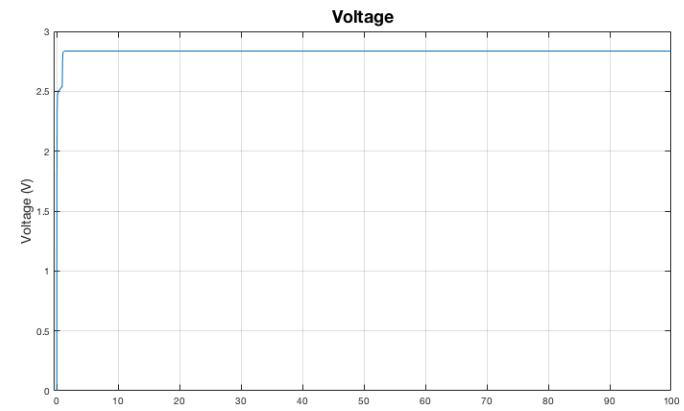
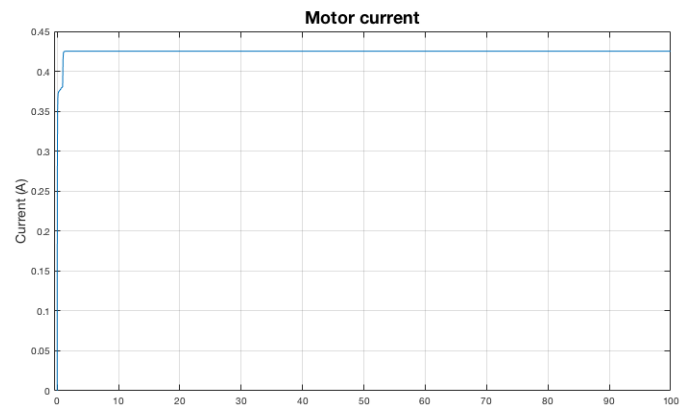
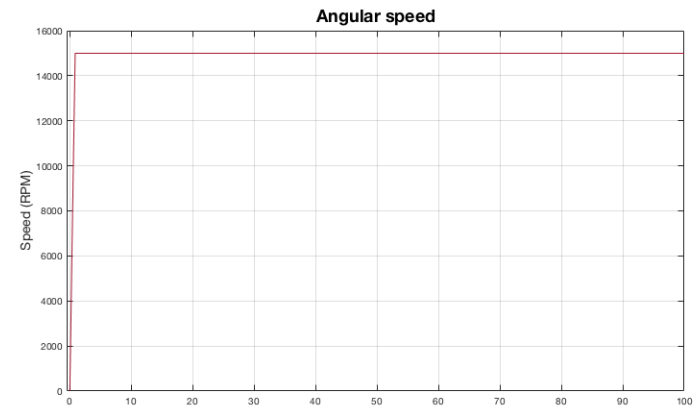
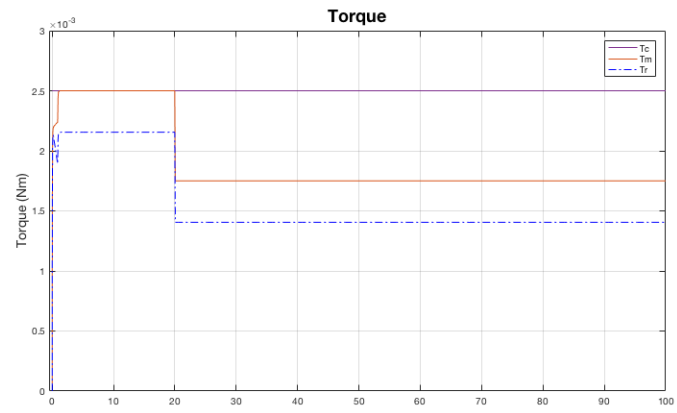
Fault 1: $k_m^{f1} = 0.7 k_m^n$

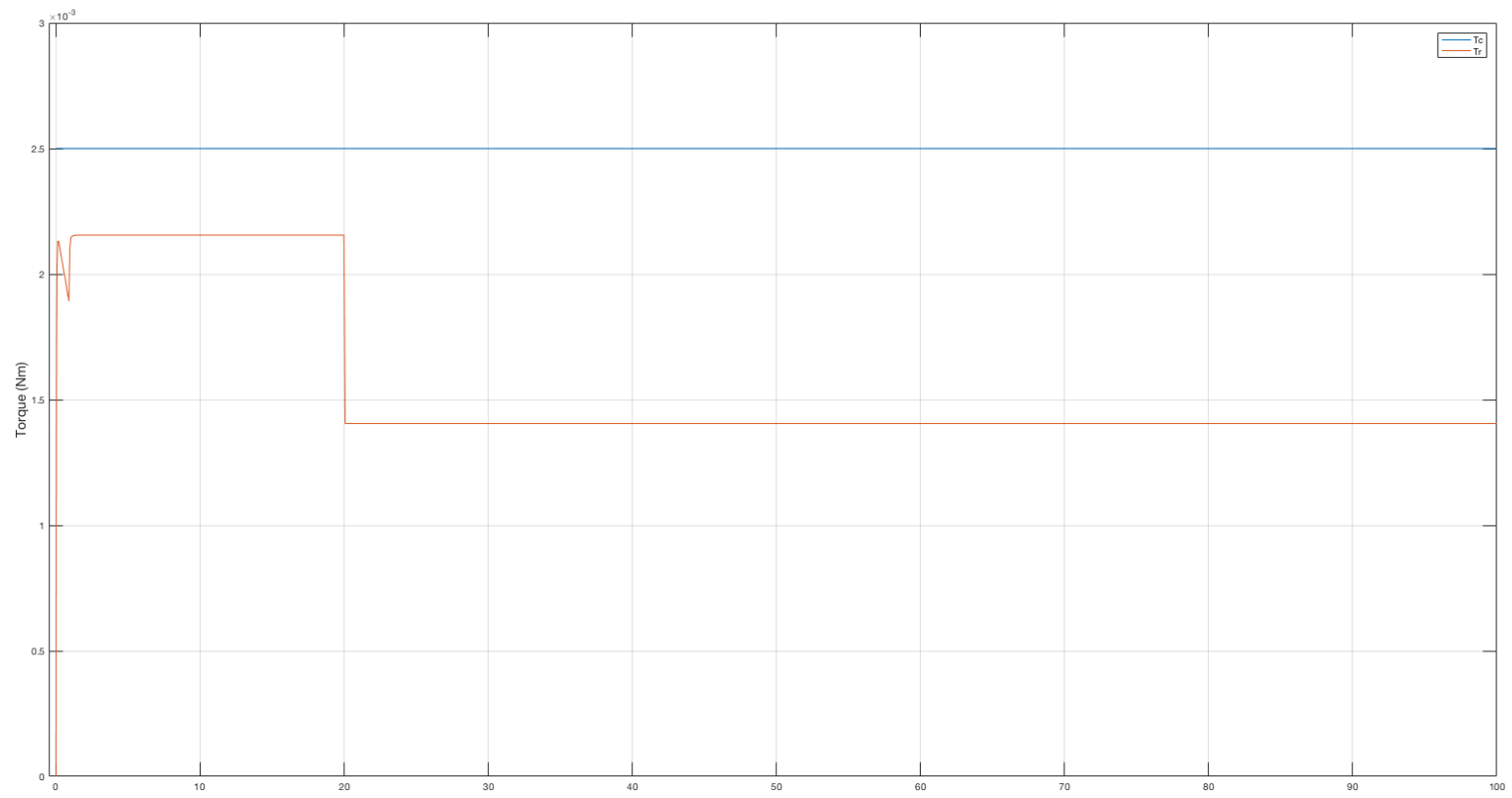




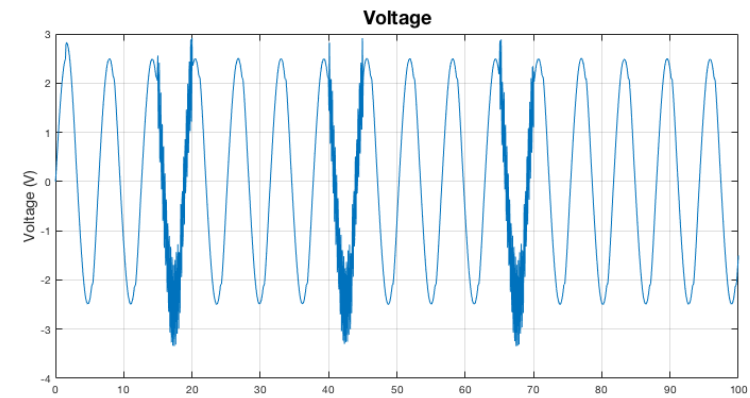
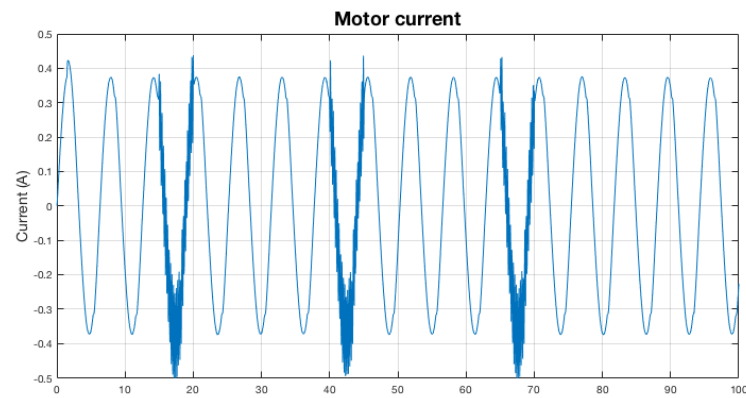
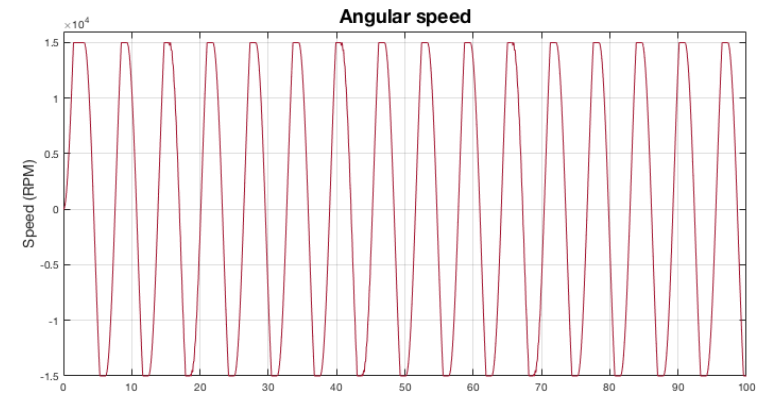
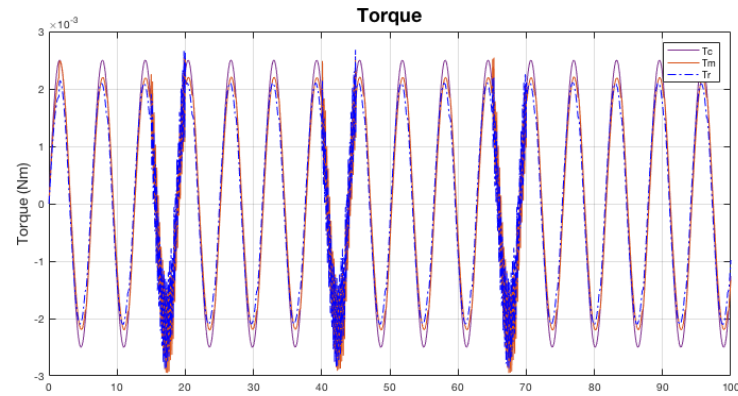


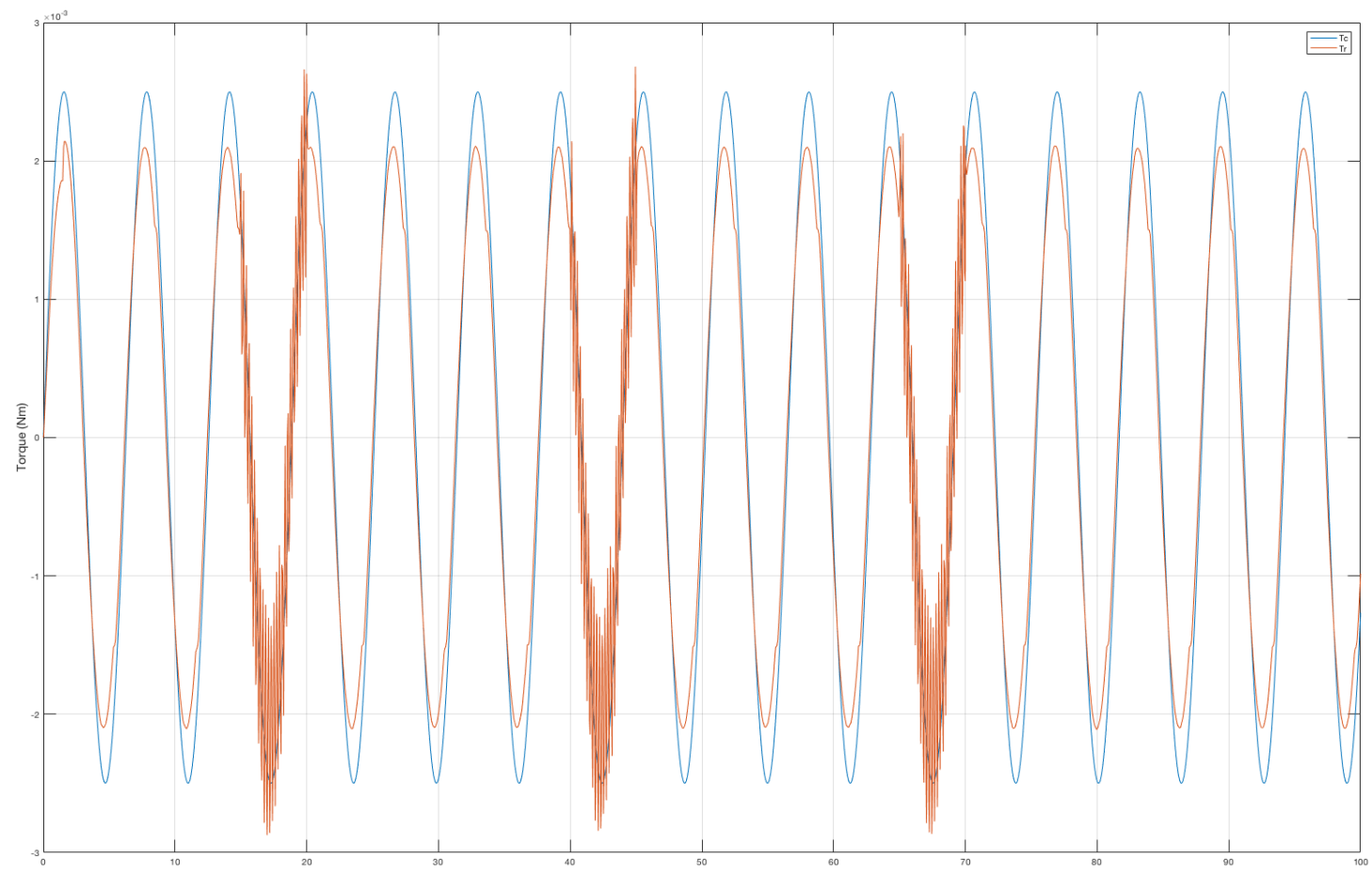


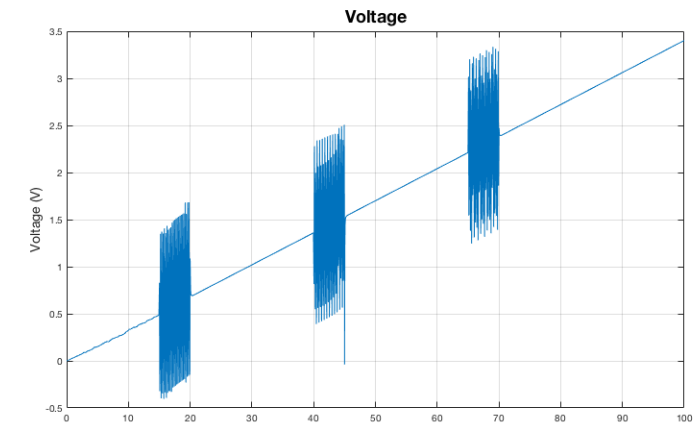
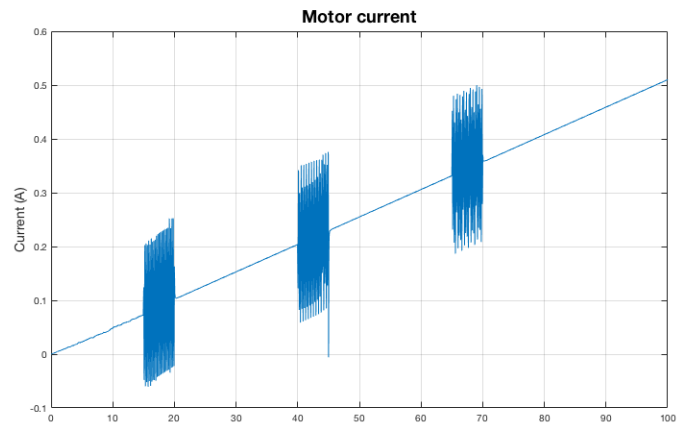
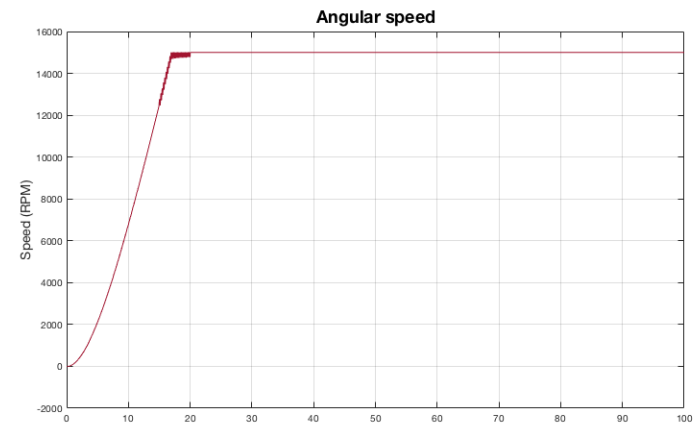
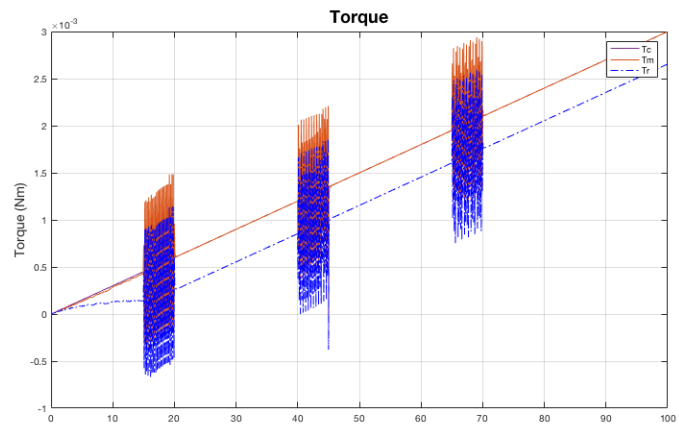


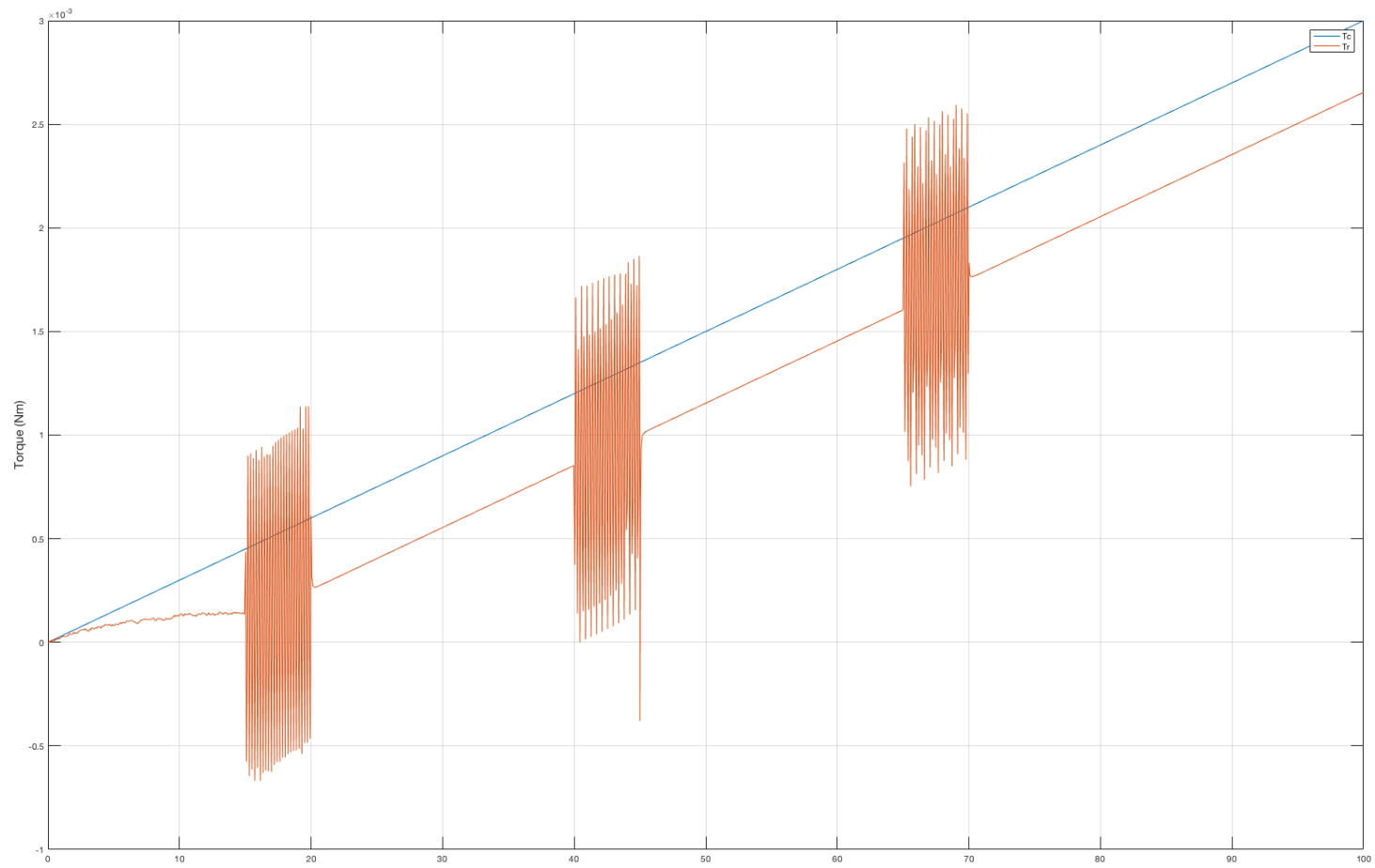


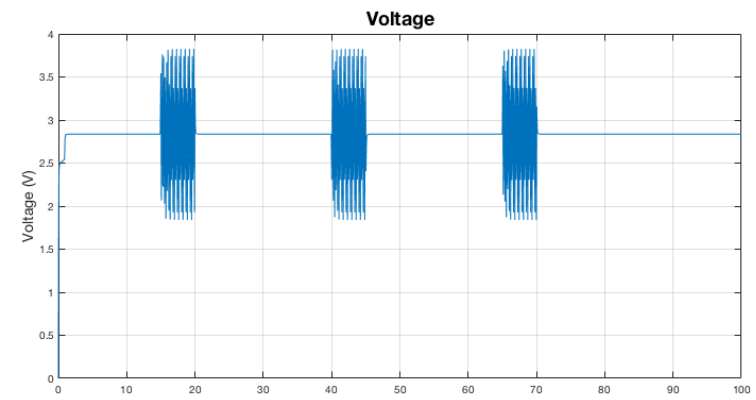
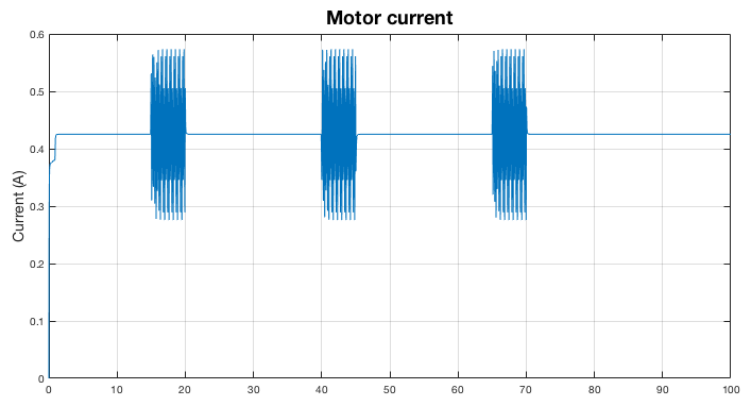
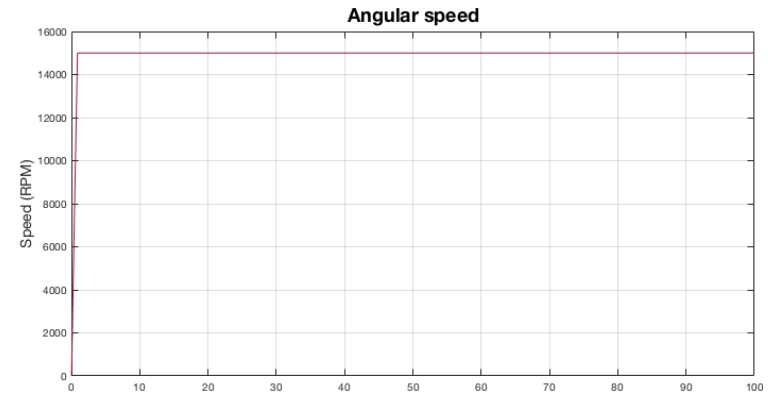
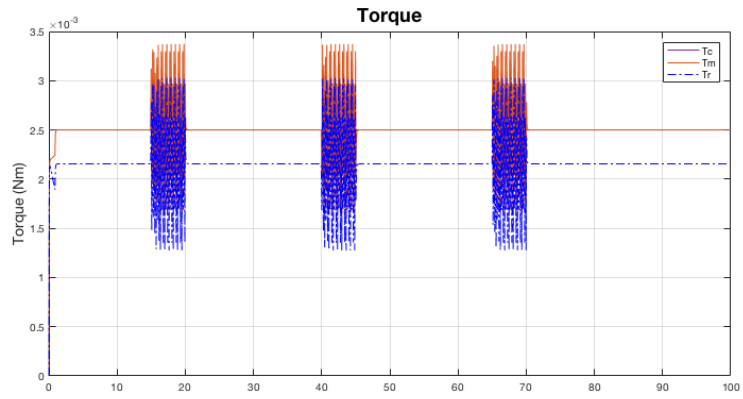
$$= 1.5 * \sin(30 * t)$$

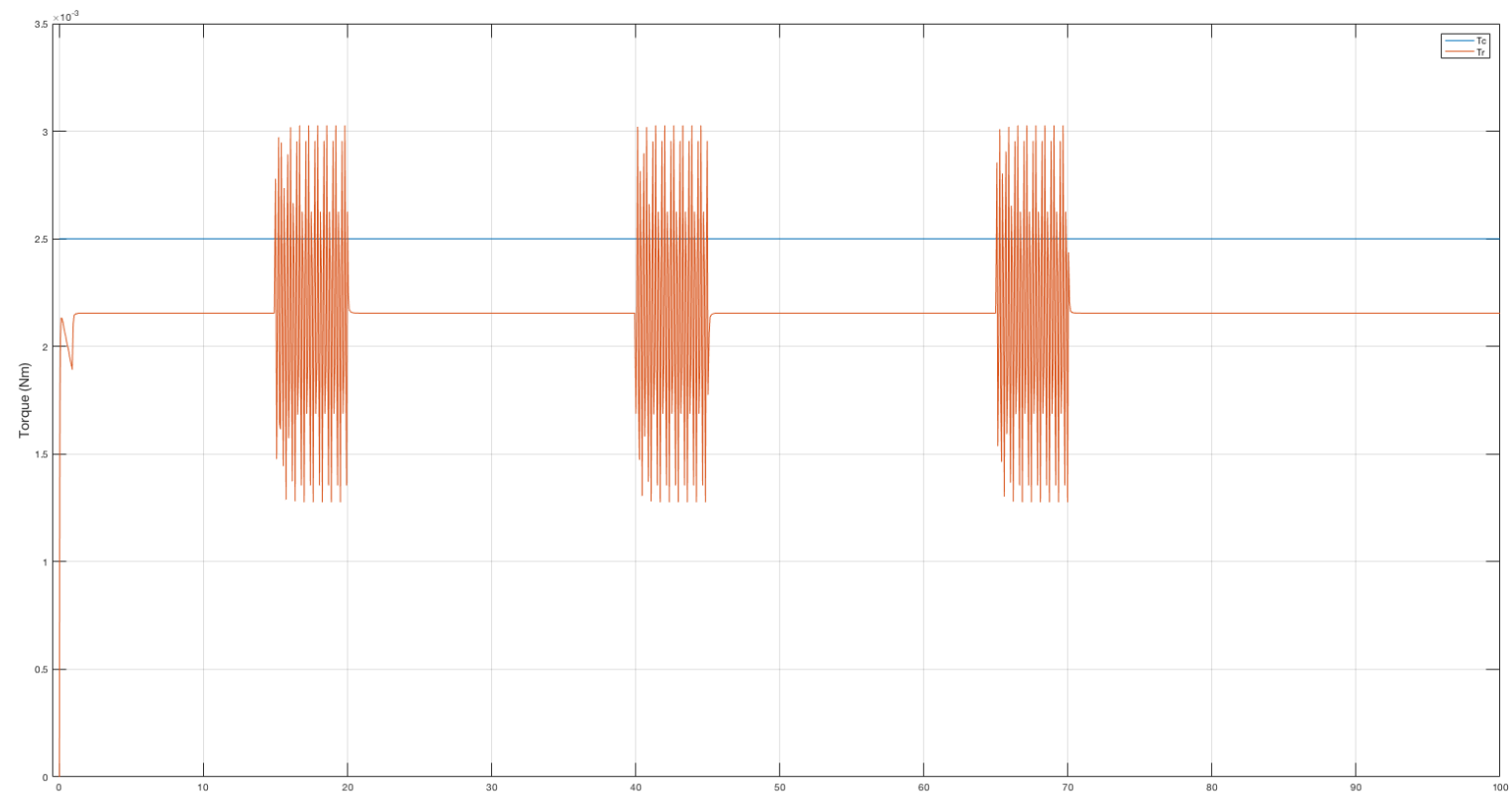




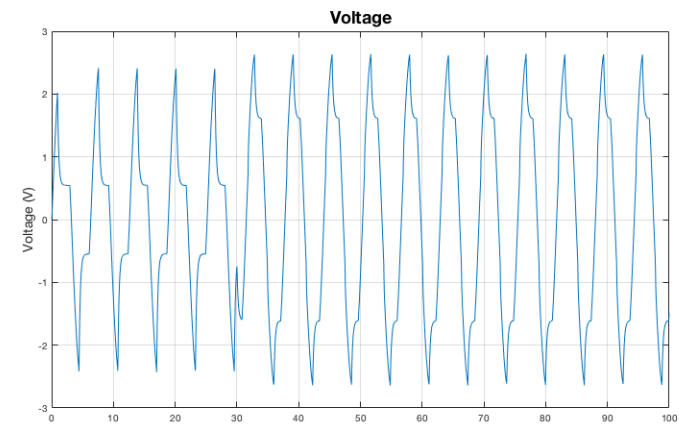
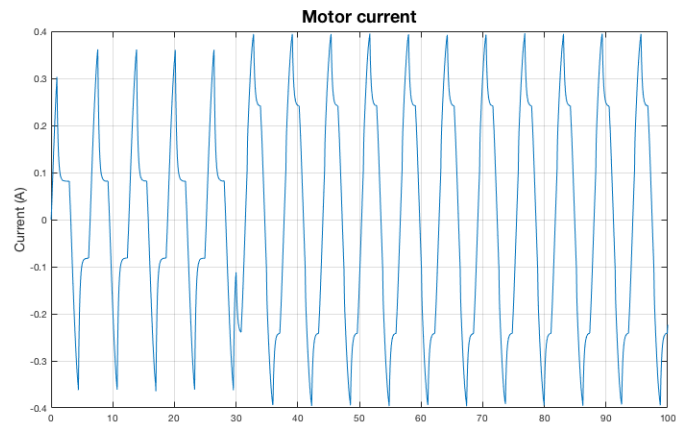
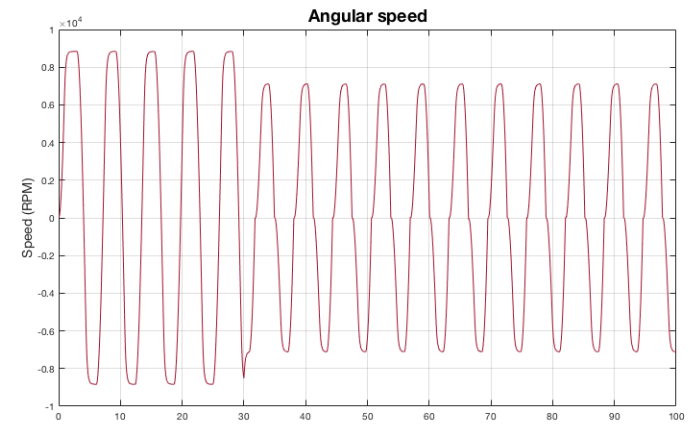
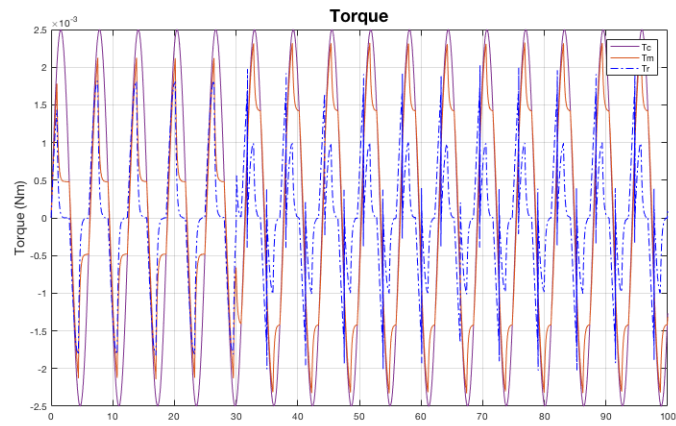


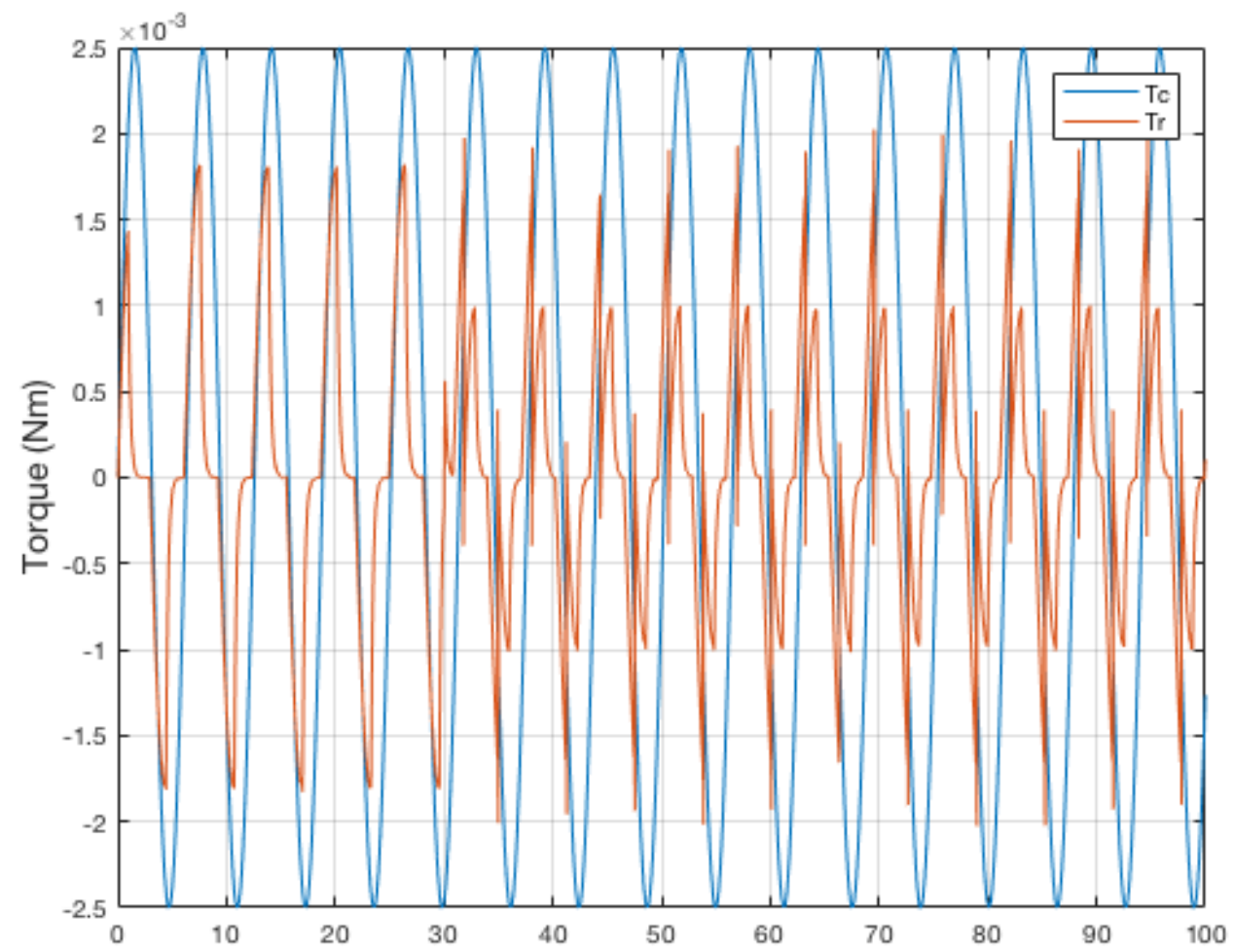


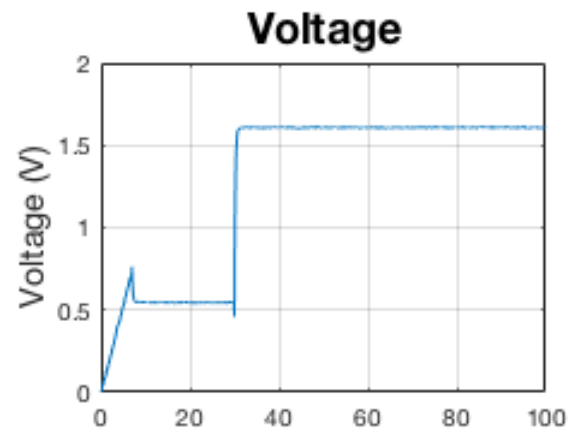
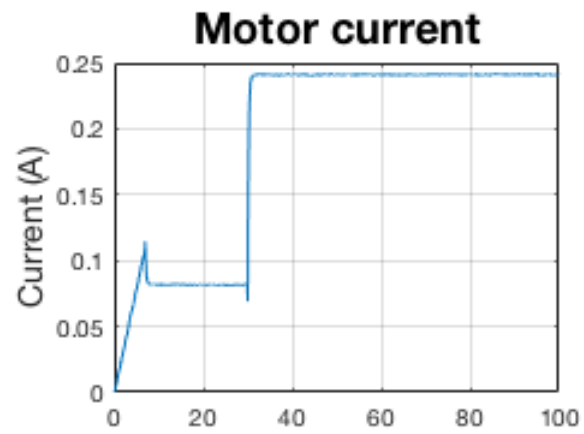
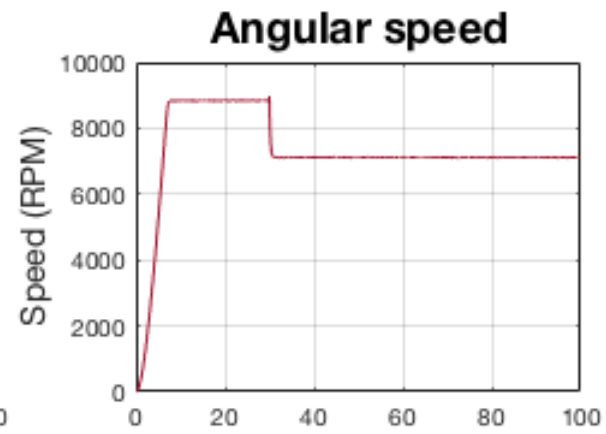
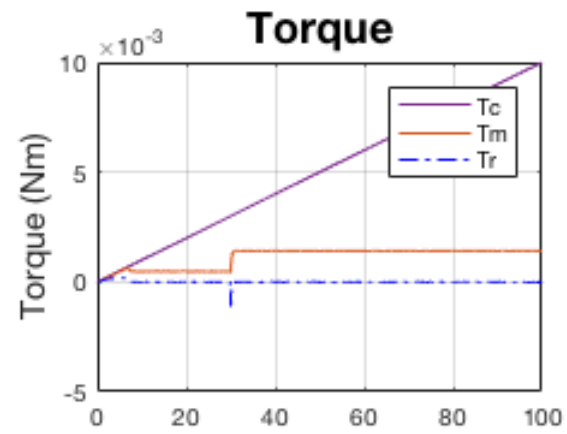


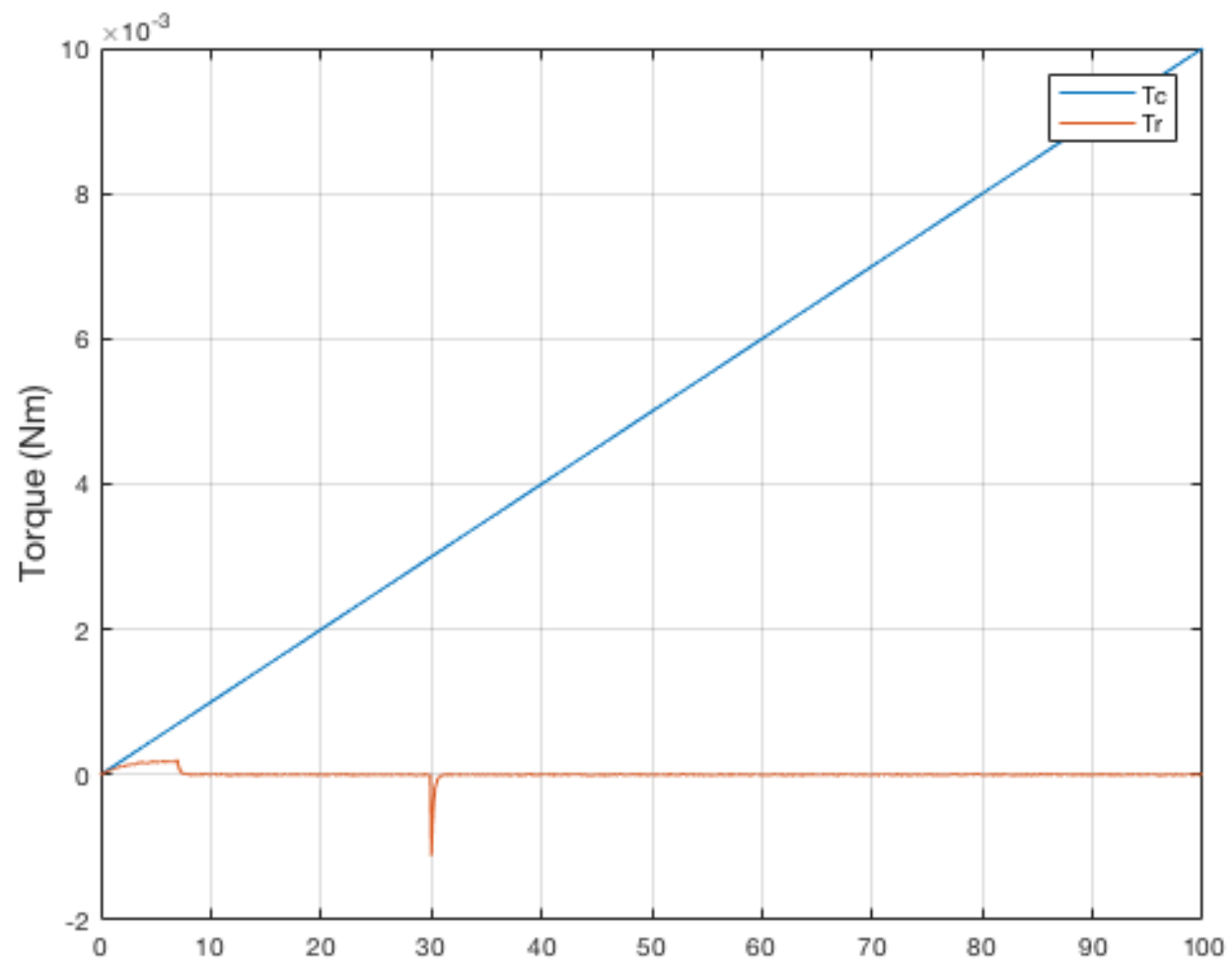


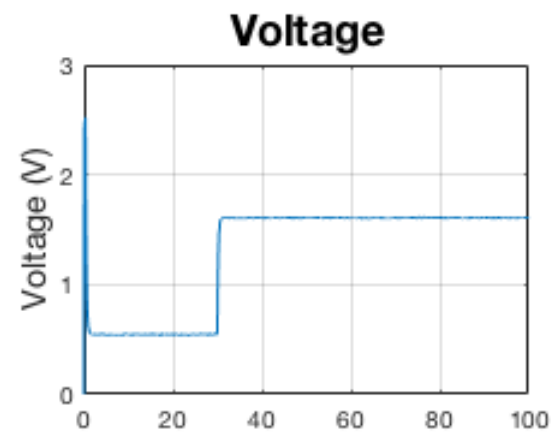
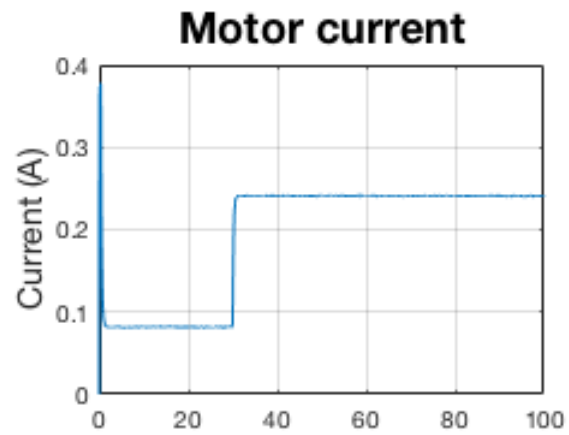
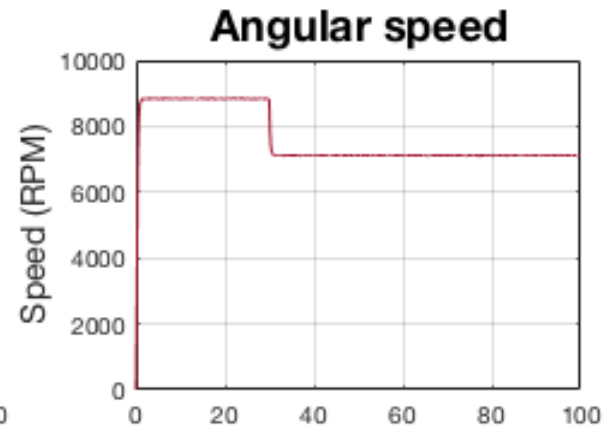
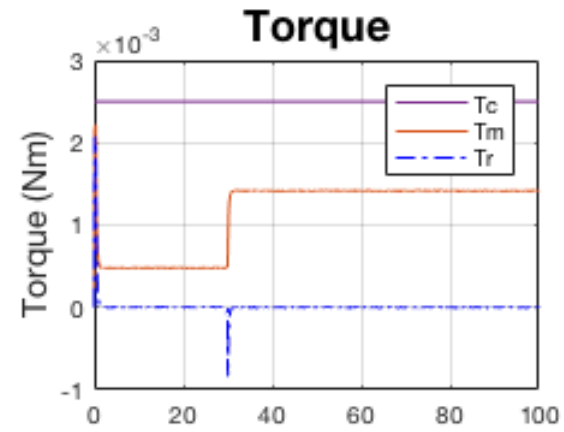
Increase

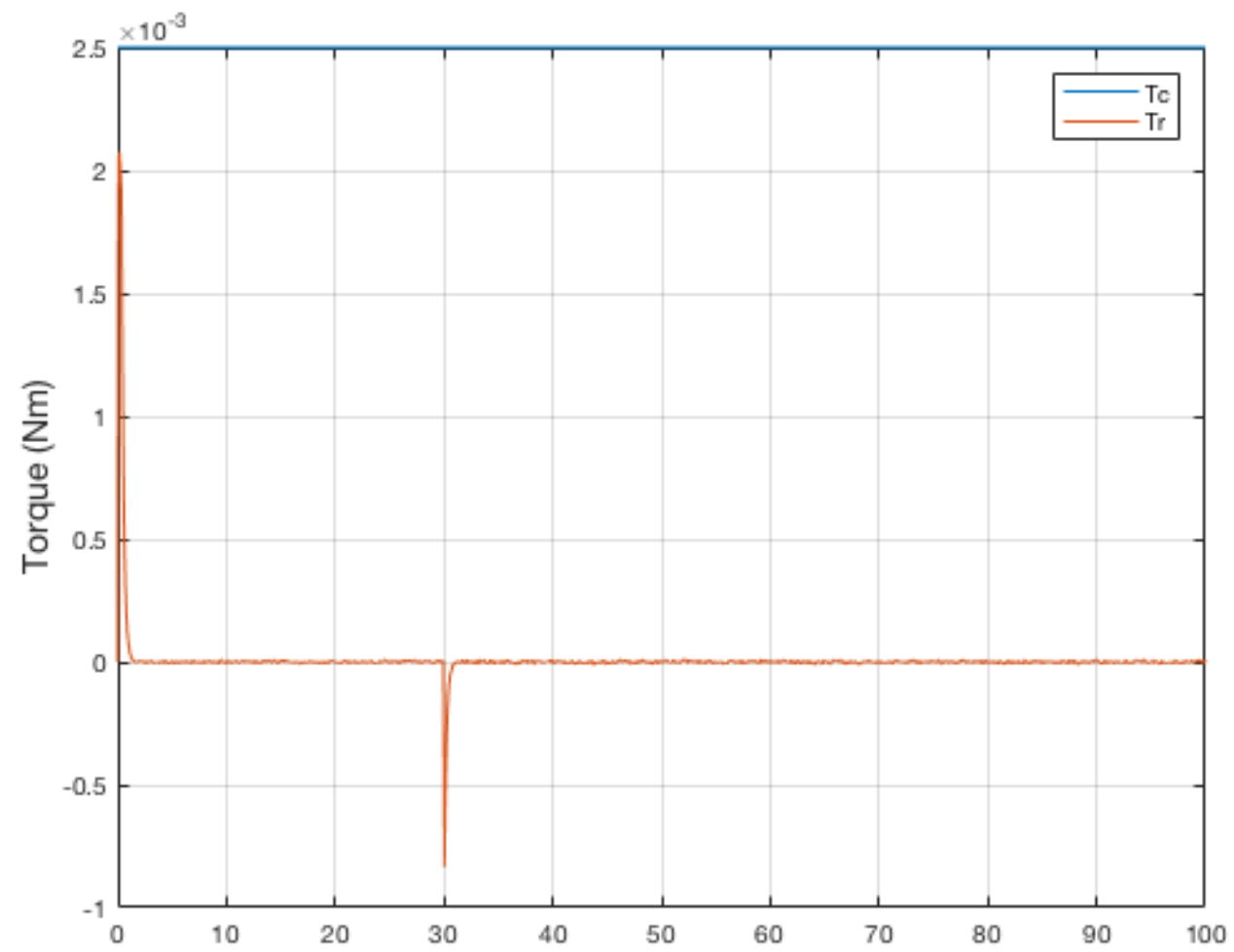




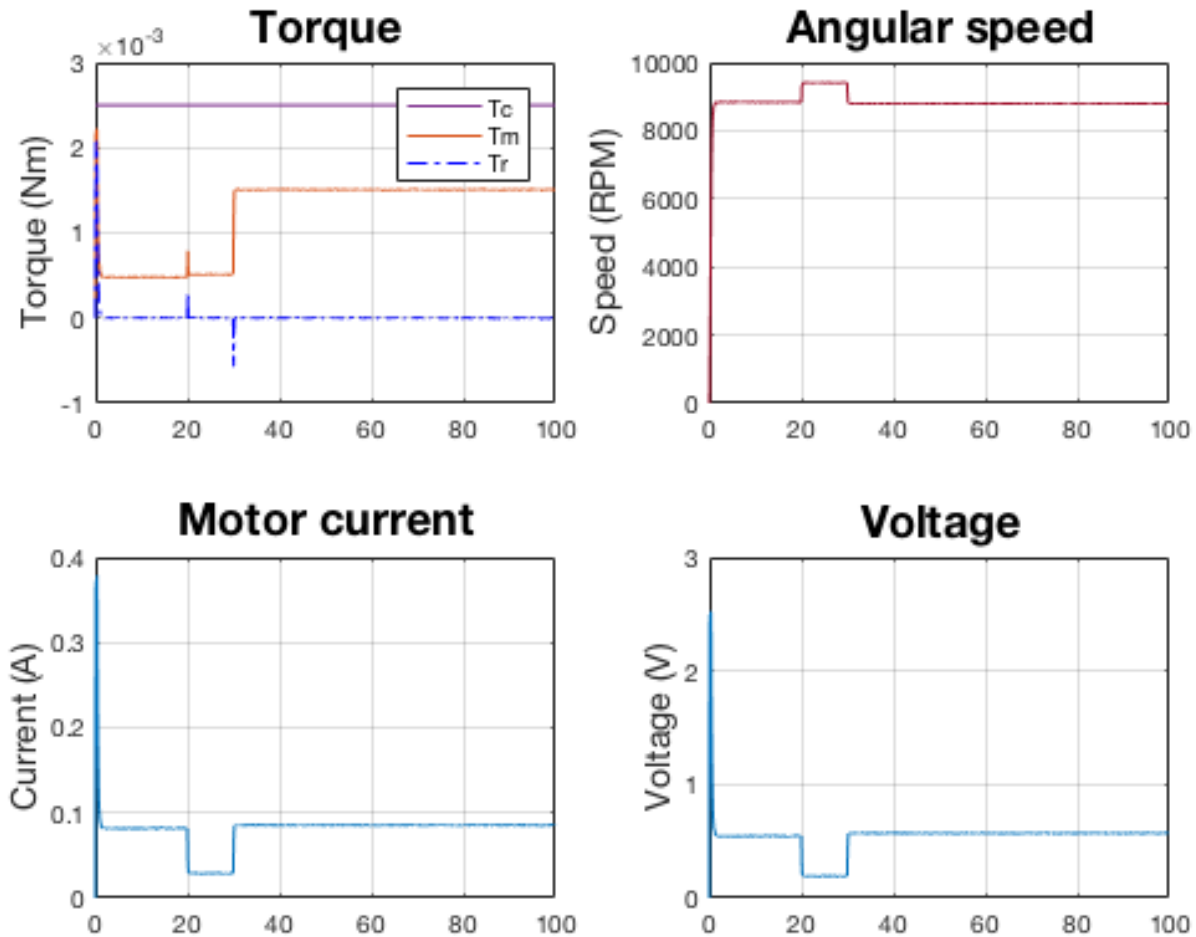


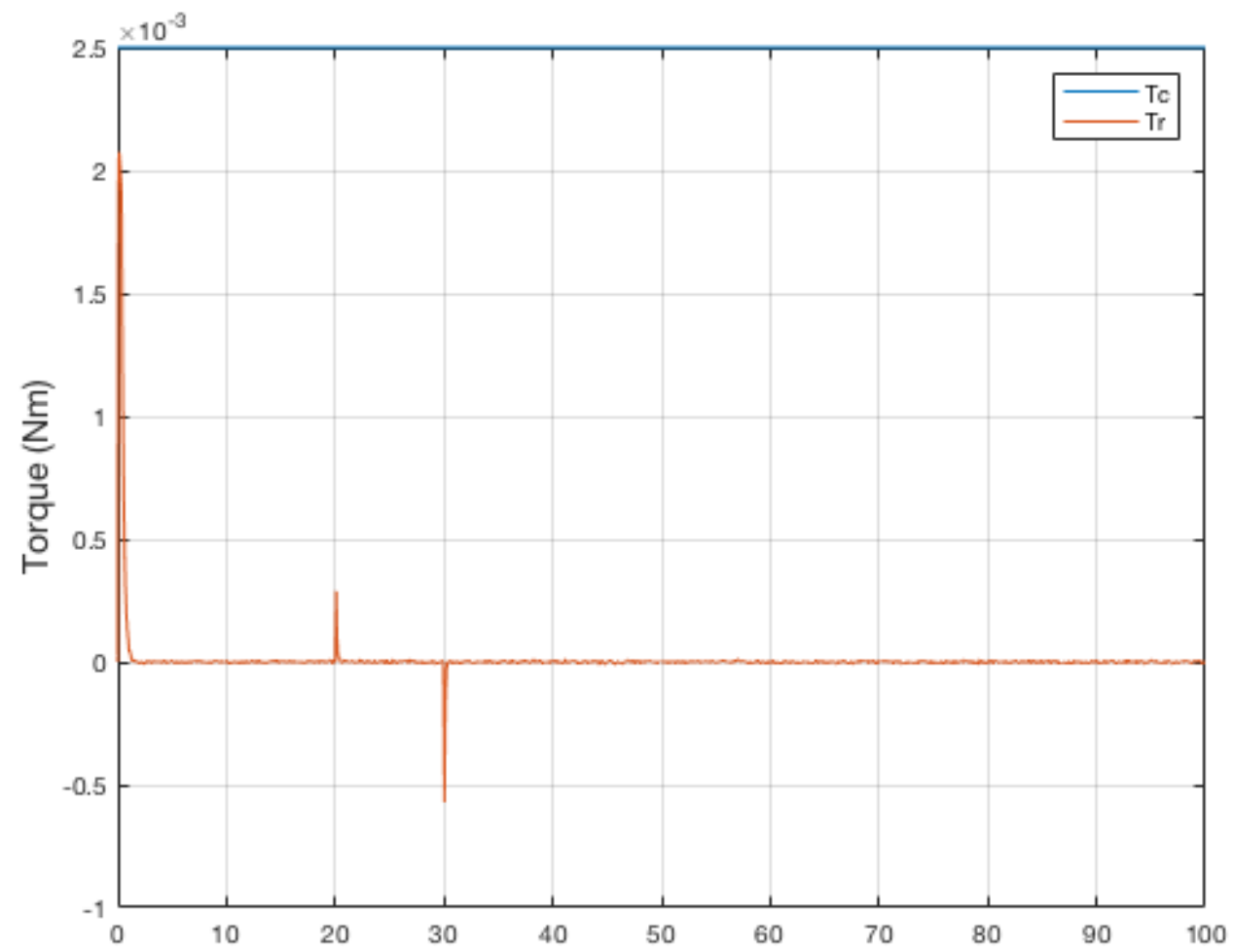


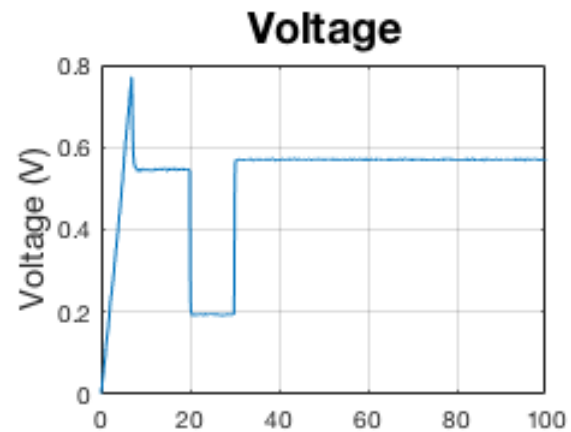
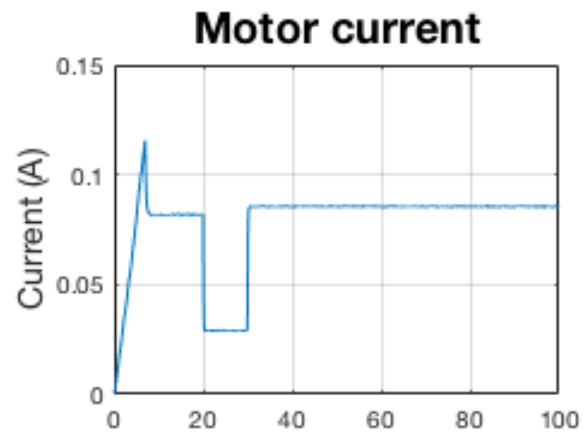
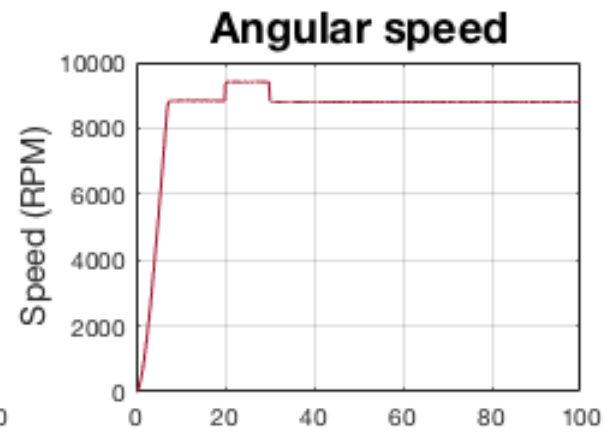
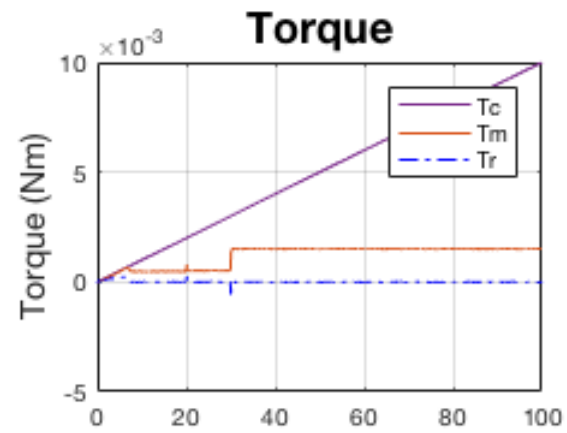


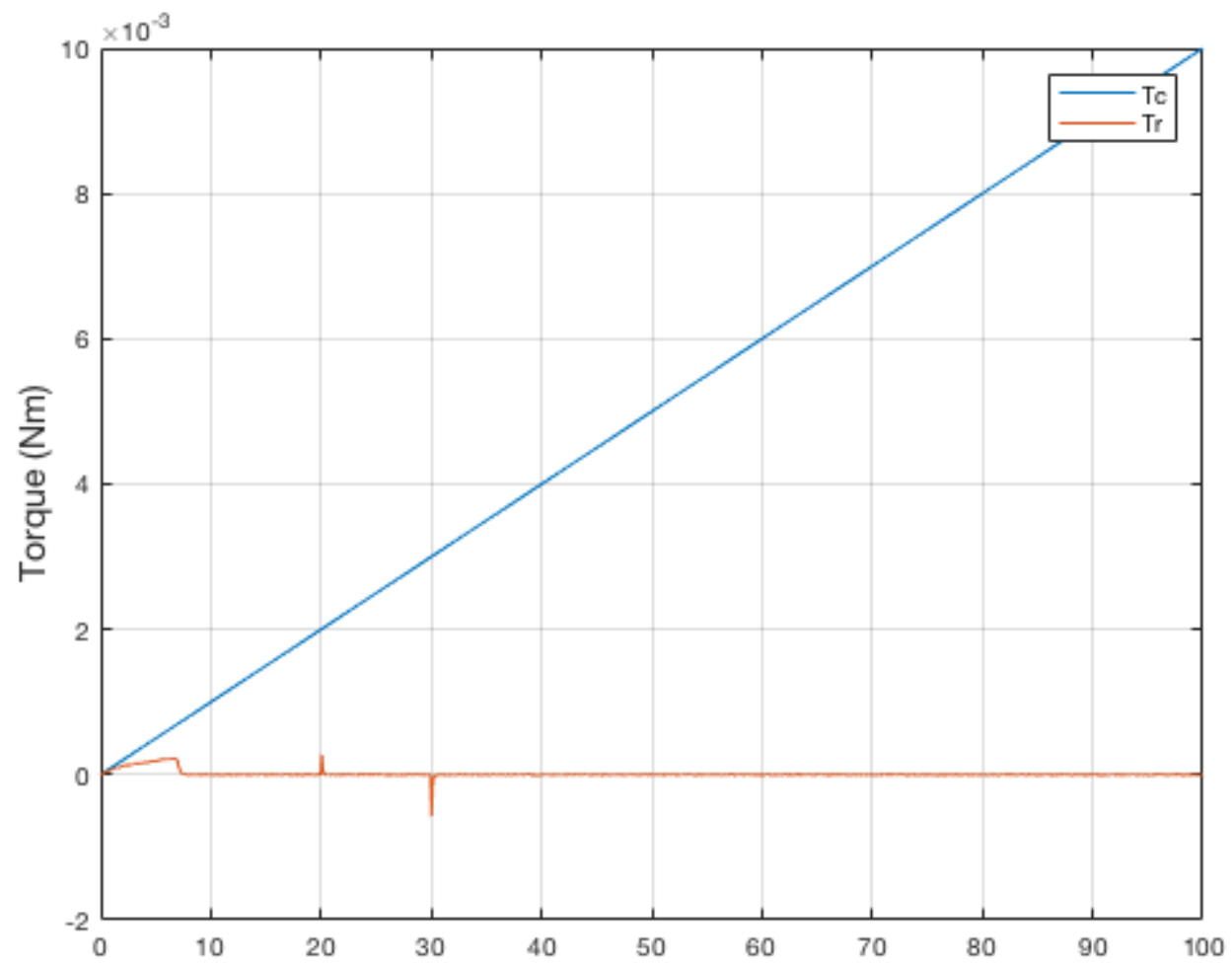


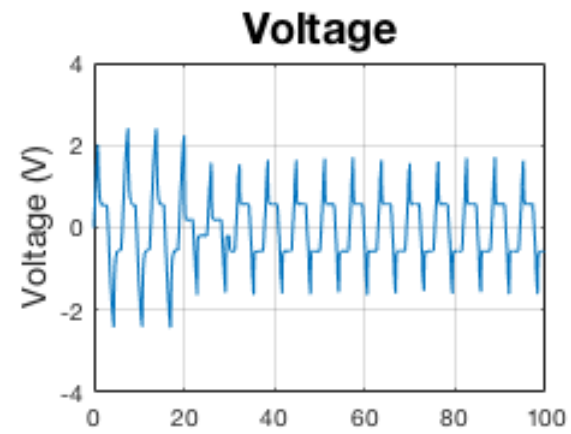
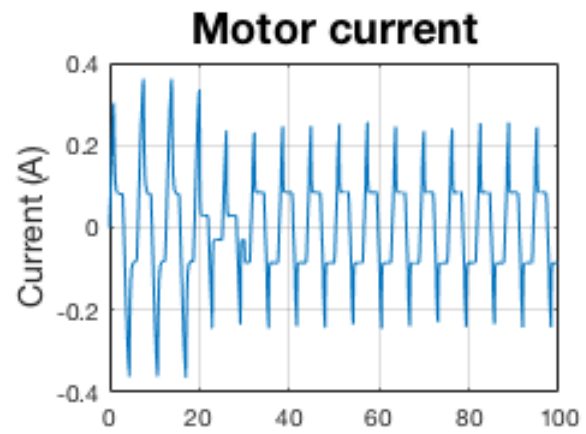
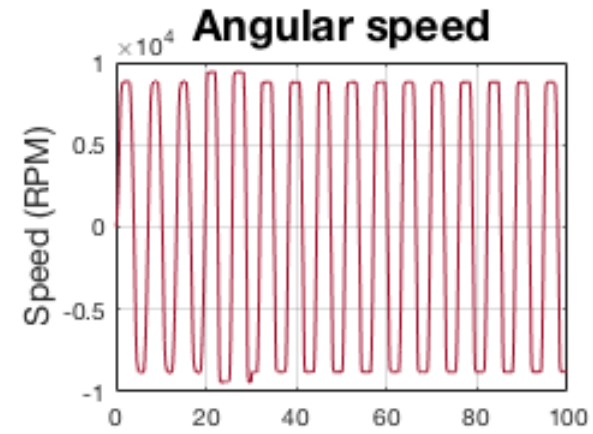
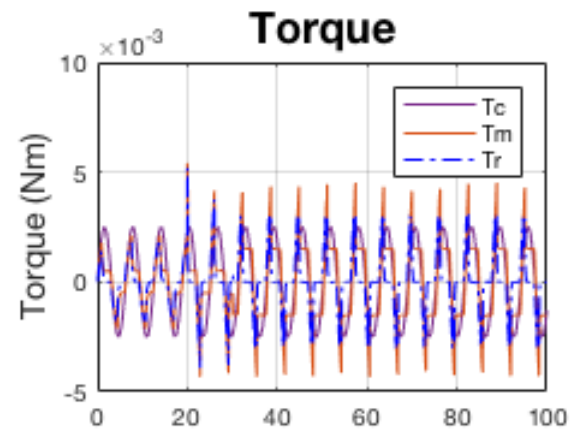
Fault 4: $k_m^{f4} = 0.7k_m^n$

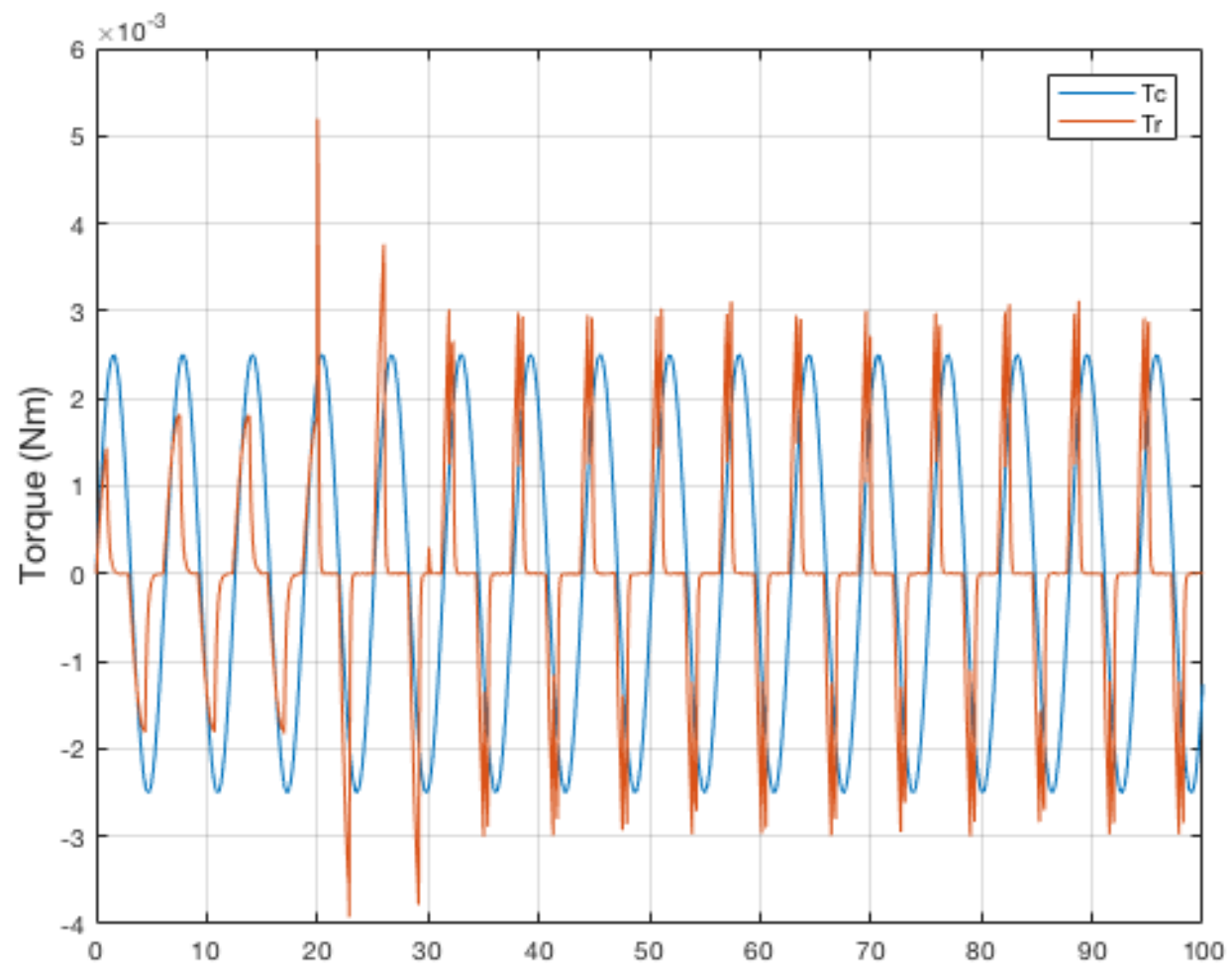




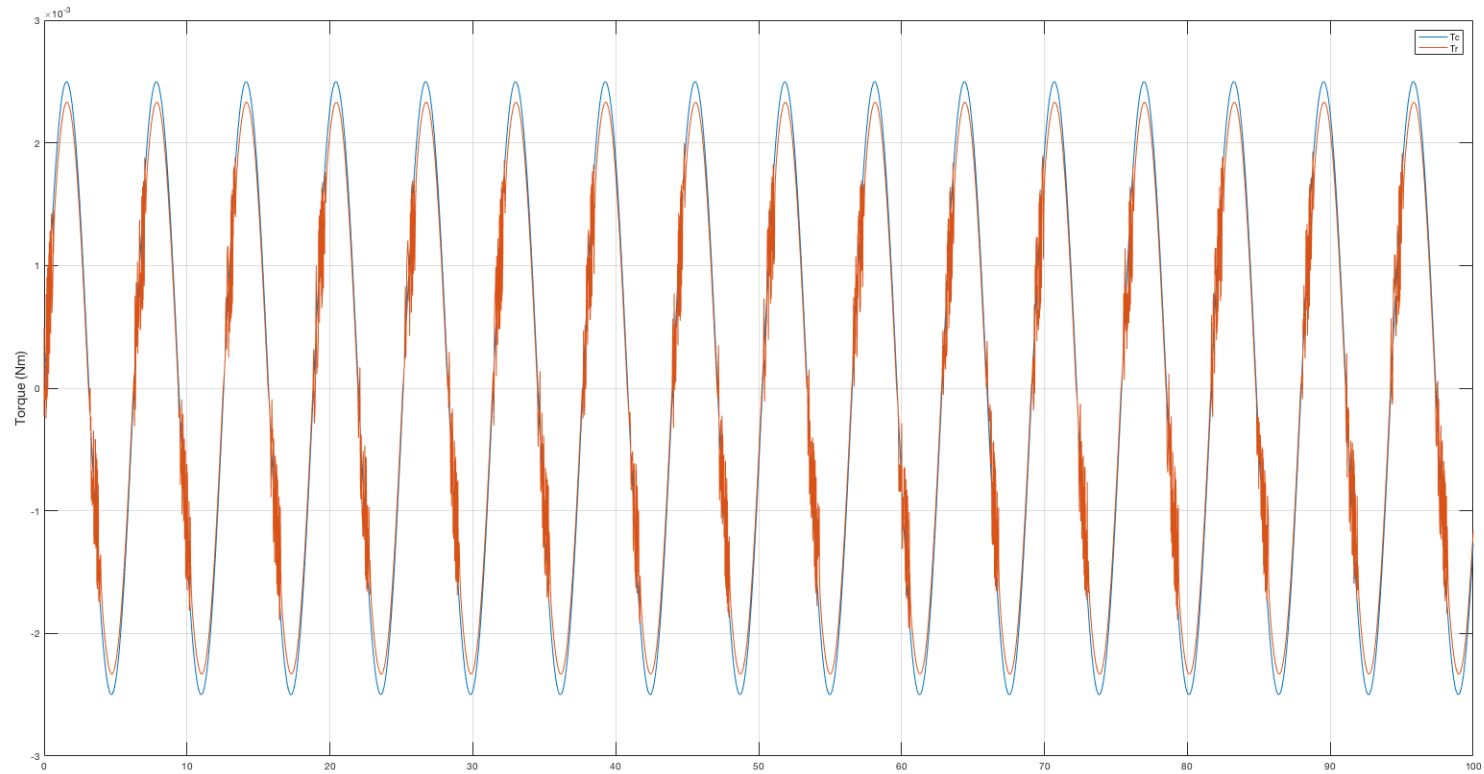






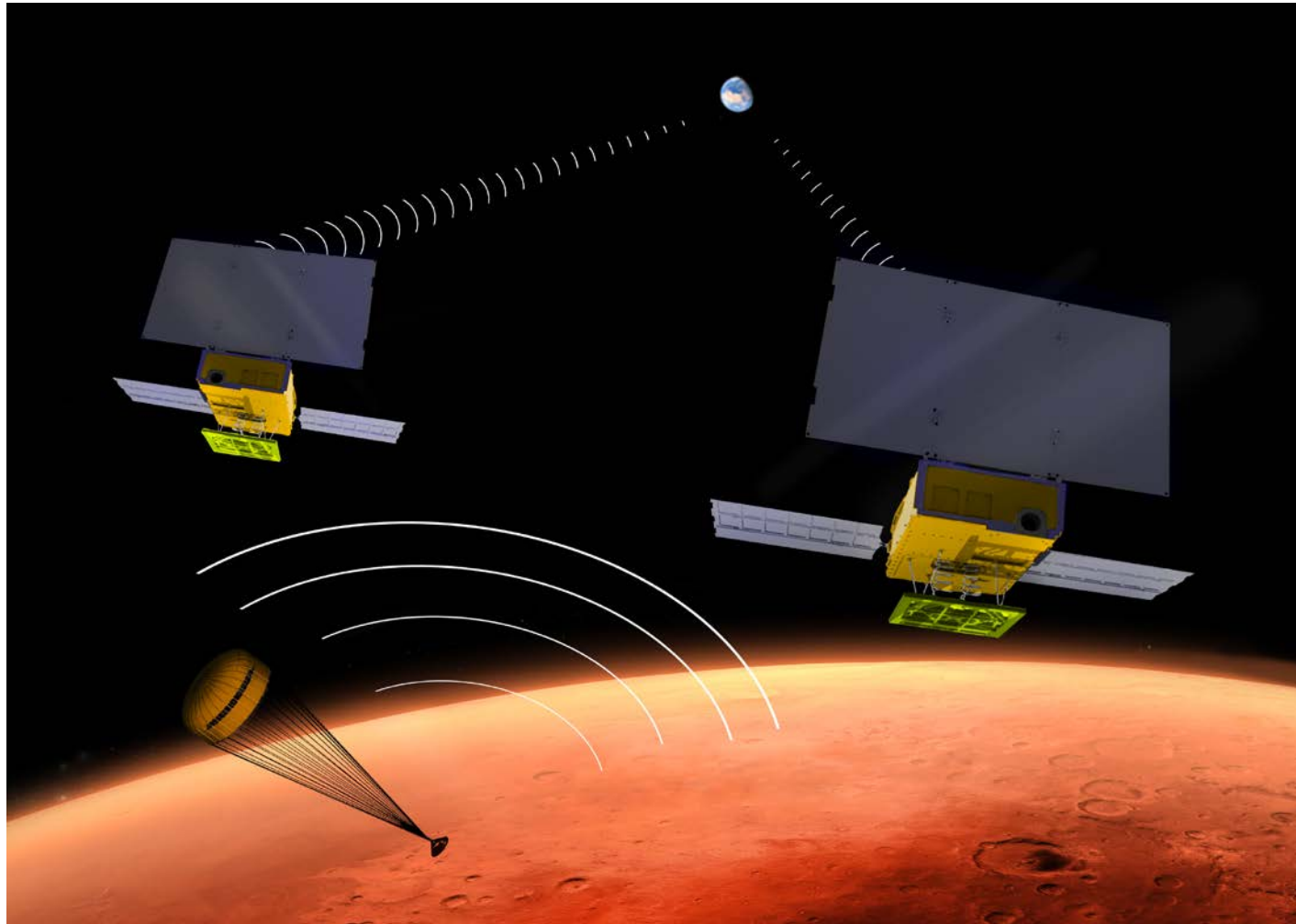


Ripple and Cogging



Next Steps

- ❑ Compare with experimental data (testbed design)
- ❑ Include spacecraft dynamics and momentum dumping devices to observe further faults
- ❑ Augmenting model with motor drive electronics
- ❑ Develop diagnostics and prognostics approach (i.e. wheel speed condition, energy consumption, etc.)



Source: NASA/JPL-Caltech

Questions?

☐ Thanks for your attention!

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