# The Science of Failure

## (Systems Health Monitoring for Satellite Systems)

Diagnostics and Prognostics Group

Discovery and Systems Health Area
Intelligent Systems Division
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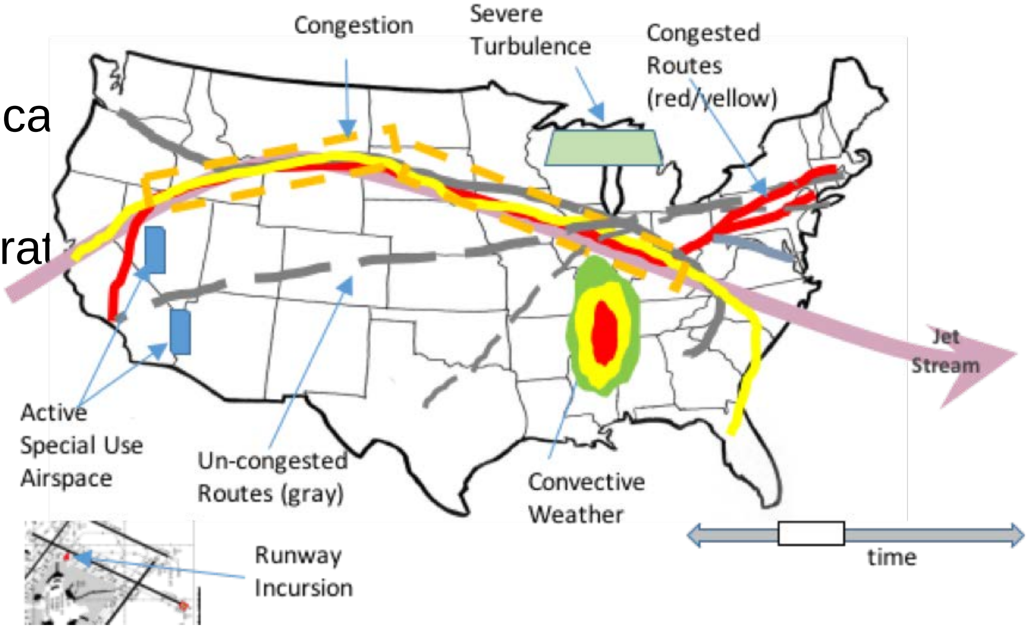
# Outline

- 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 foreca NAS state
  - Interact with multiple independent tools and mentally integrat 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

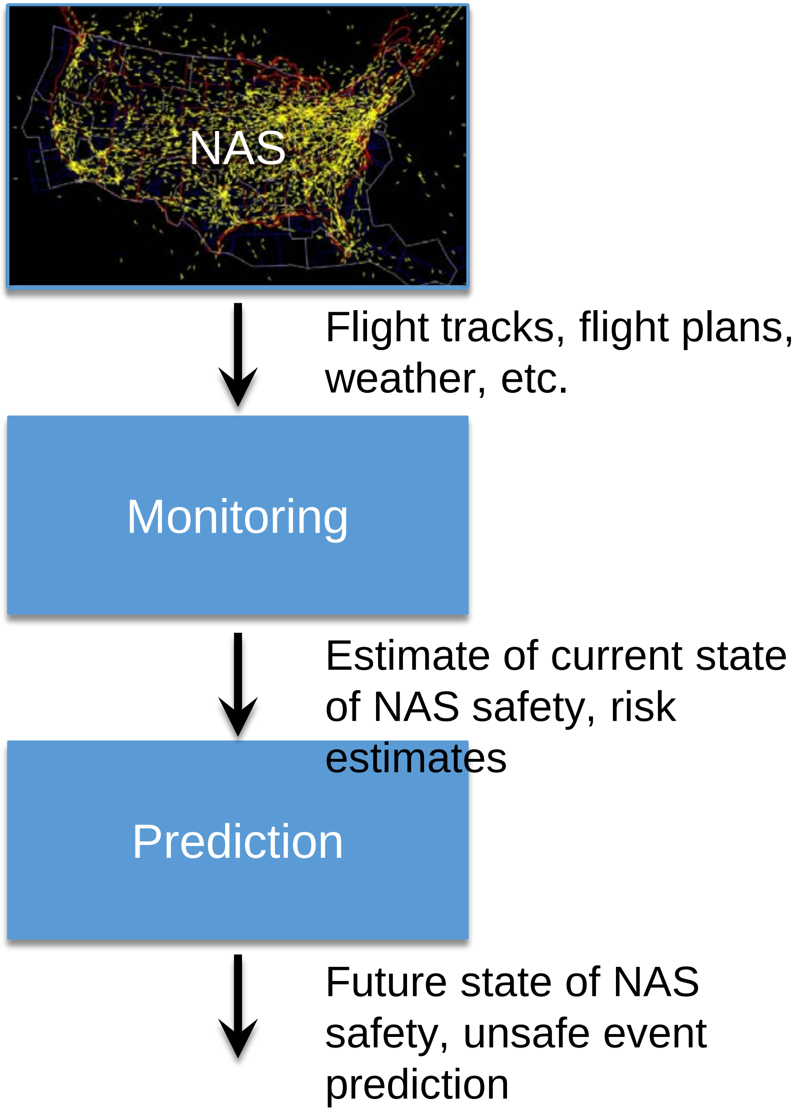


# Research Goals

- 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?



NAS

Flight tracks, flight plans, weather, etc.

Monitoring

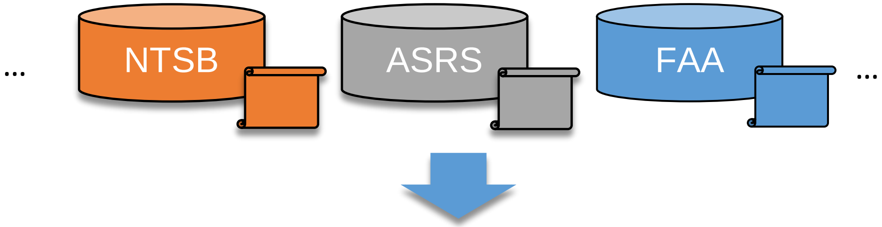
Estimate of current state of NAS safety, risk estimates

Prediction

Future state of NAS safety, unsafe event prediction

# 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

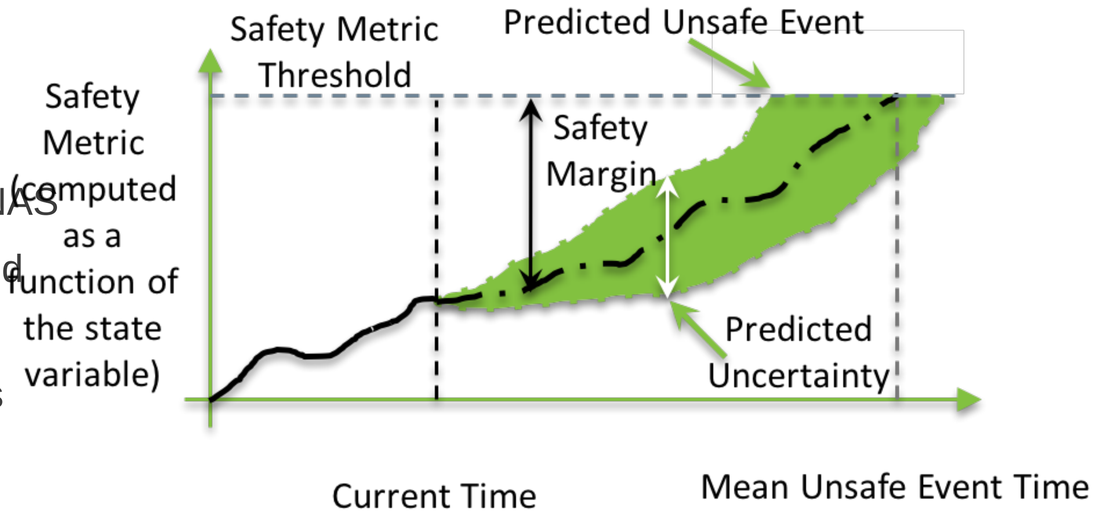


Hazards
- Inoperative Navaid
- Excessive Communication
- Procedure Complexity
- Low Visibility
- Turbulence
- Icing

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

# Definitions

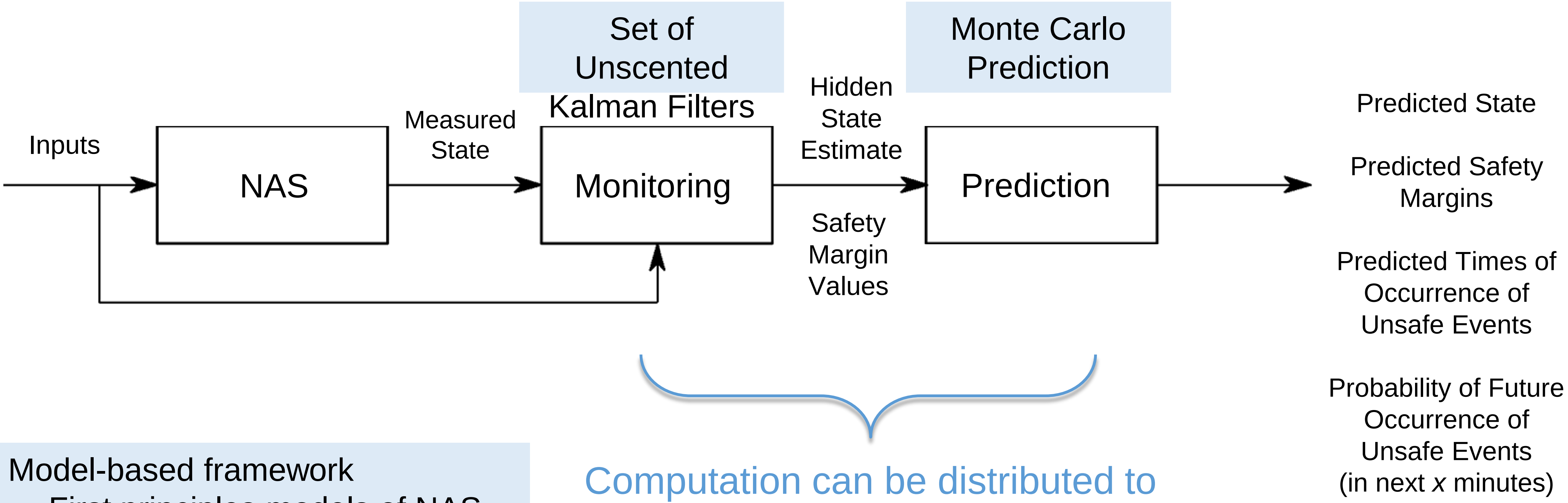
- ***Unsafe event***: An event/situation that compromises NAS safety or established safety standards
    - Examples: loss of separation, loss of control, controlled flight into terrain, runway incursion, hard landing, tail strike, collision, etc.
- ***Hazard***: A condition that potentially contributes 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?
  - Margin = {“distance” to event threshold}/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



Set of Unscented Kalman Filters

Monte Carlo Prediction

Inputs

NAS

Measured State

Monitoring

Hidden State Estimate

Safety Margin Values

Prediction

Predicted State

Predicted Safety Margins

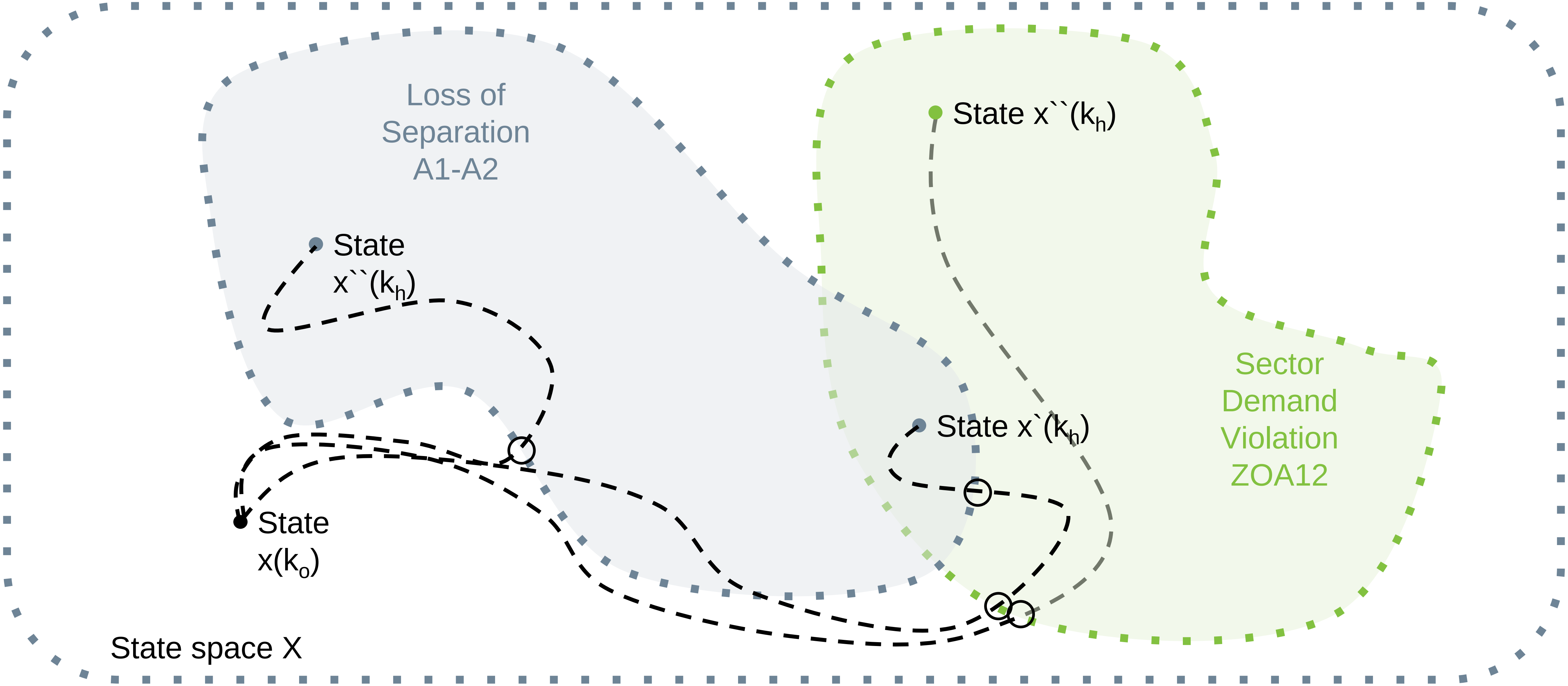
Predicted Times of Occurrence of Unsafe Events

Probability of Future Occurrence of Unsafe Events (in next *x* minutes)

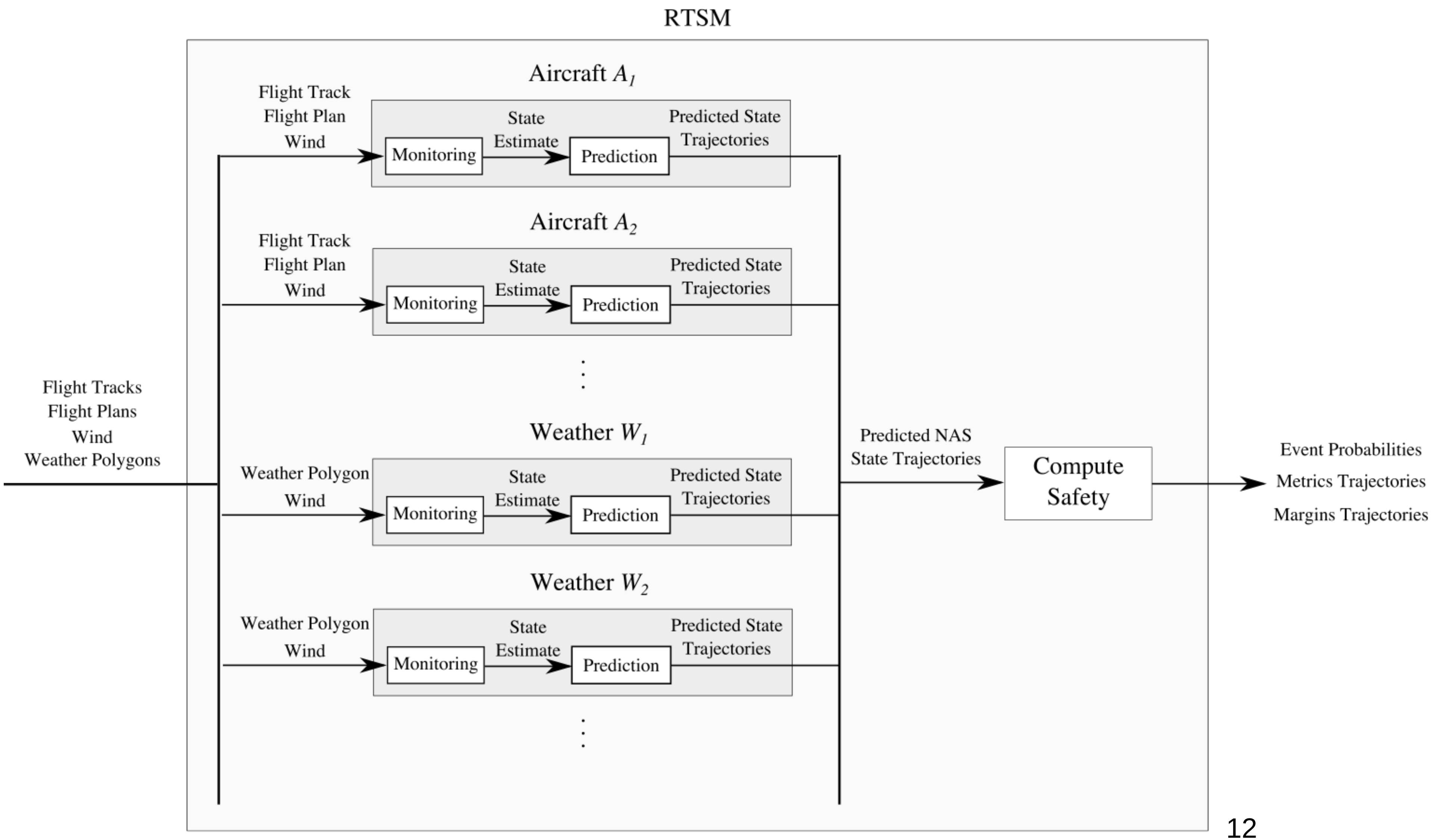
Model-based framework
- First principles models of NAS components (aircraft dynamics, weather, wake vortex, etc.)
- Safety metrics & thresholds

Computation can be distributed to different regions of the NAS and consolidated for system-level safety assessment

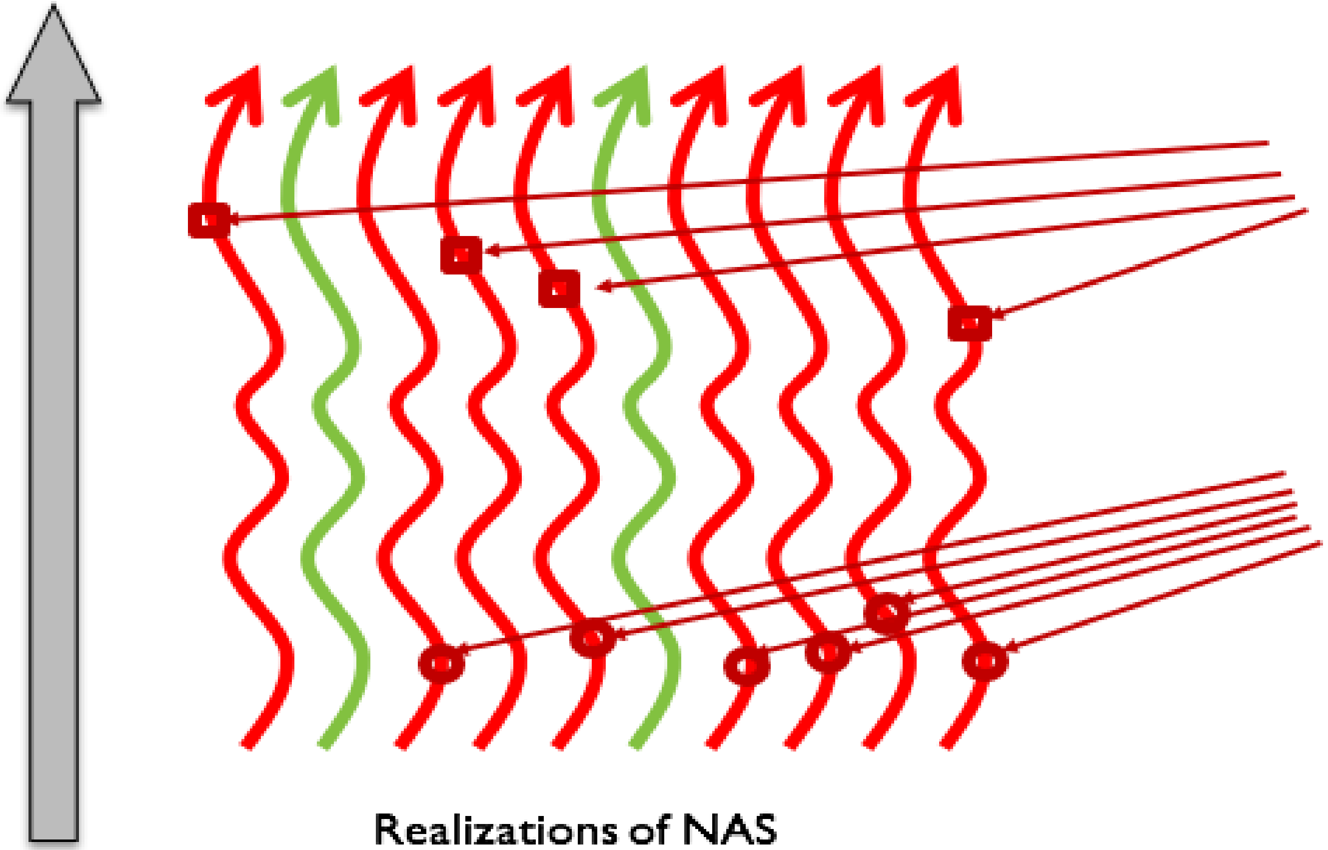
# Conceptual Framework



# 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

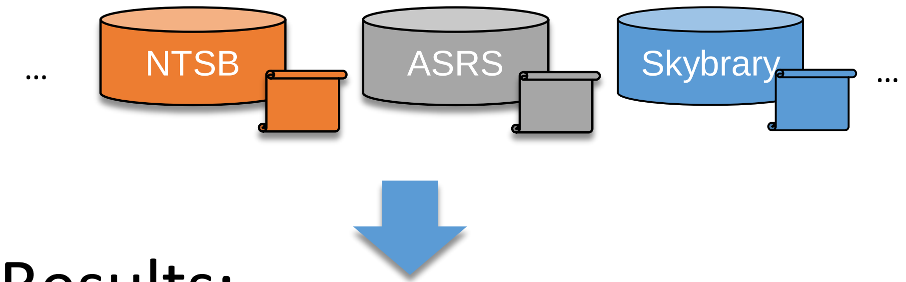
# Extension to Airport Surface Operations

# Motivation

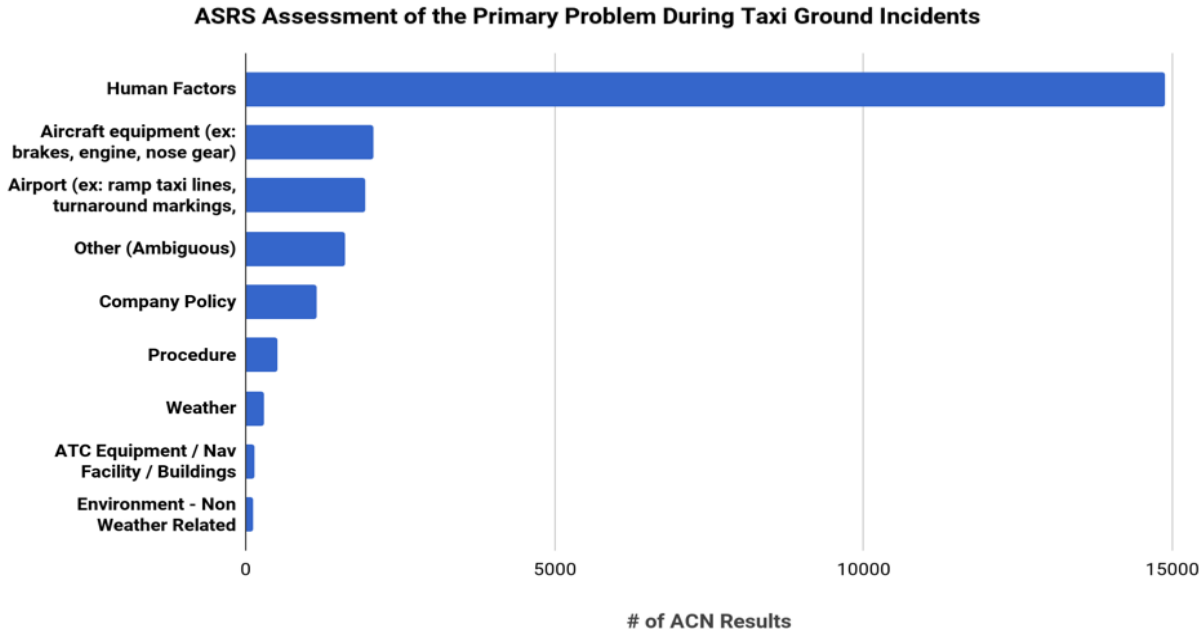
> *"While commercial aviation has made extraordinary strides in safety, one area where risk remains is on the airport surface. The bottom line is planes shouldn't run into each other in the air or on the ground."*
>
> \- NTSB Spokesman

# 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 framework[1] 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. CEN11IA270

# 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 Incidents[1]
  - 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 | rwyContamination.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% | Data required for the helper functions |

# Airport Reconfiguration

# Motivation

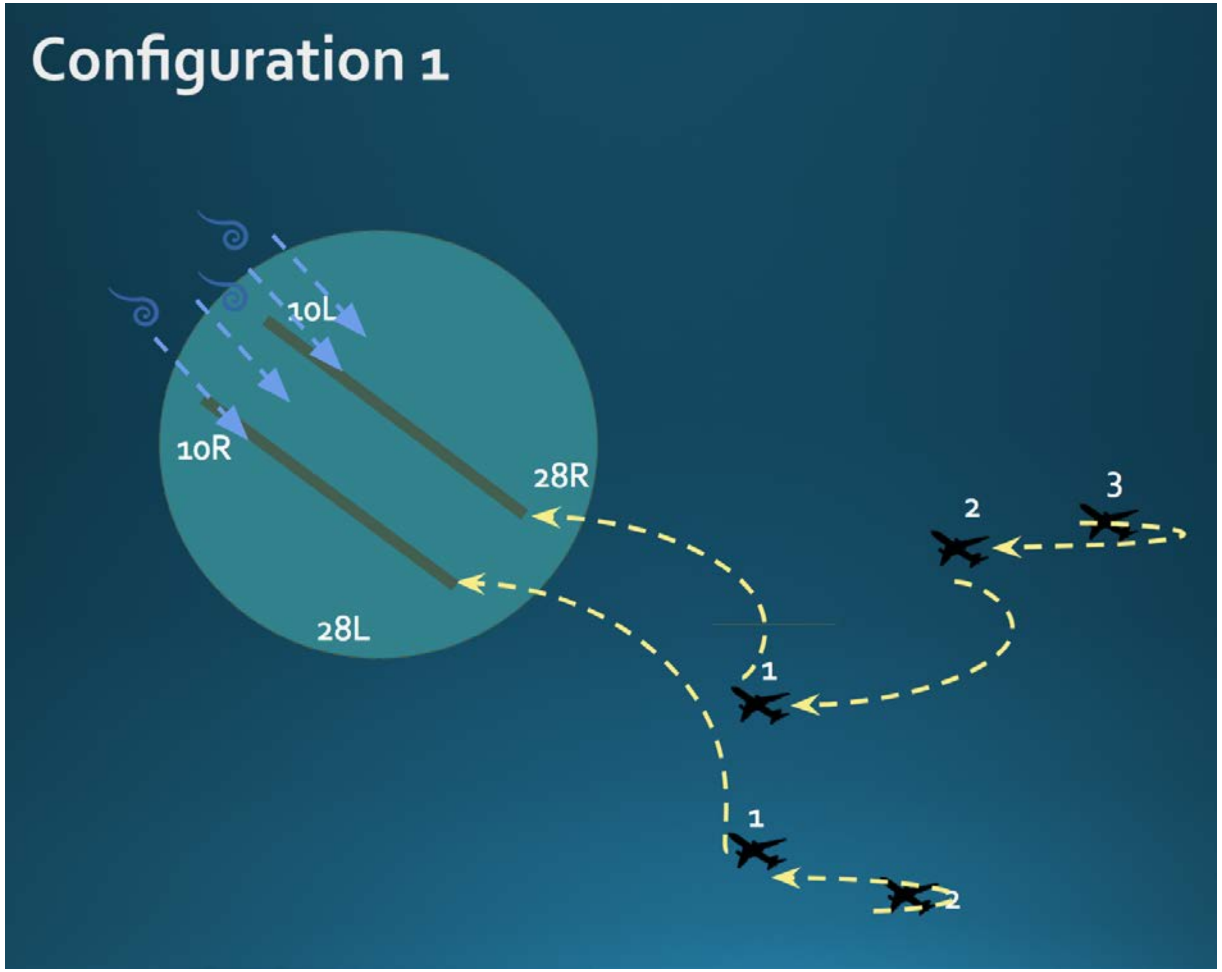
- Runway configurations depend on current and predicted traffic demand, wind speed and direction coordinated between controllers, pilots, and ground personnel
- Can be disruptive and challenging for human decision makers
- Optimization methods do not systematically handle uncertainty associated with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

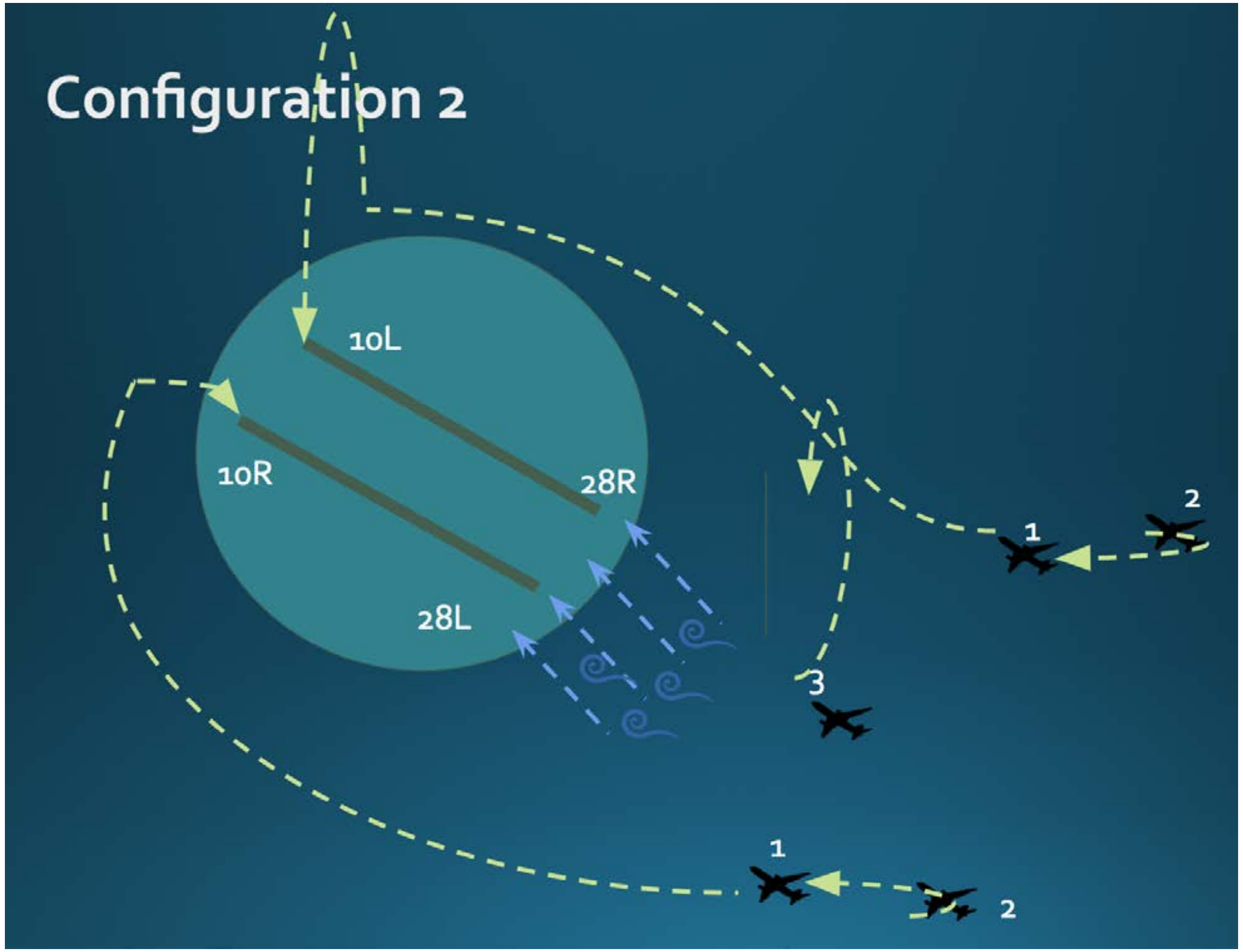
Approach: Markov Decision Process

# 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

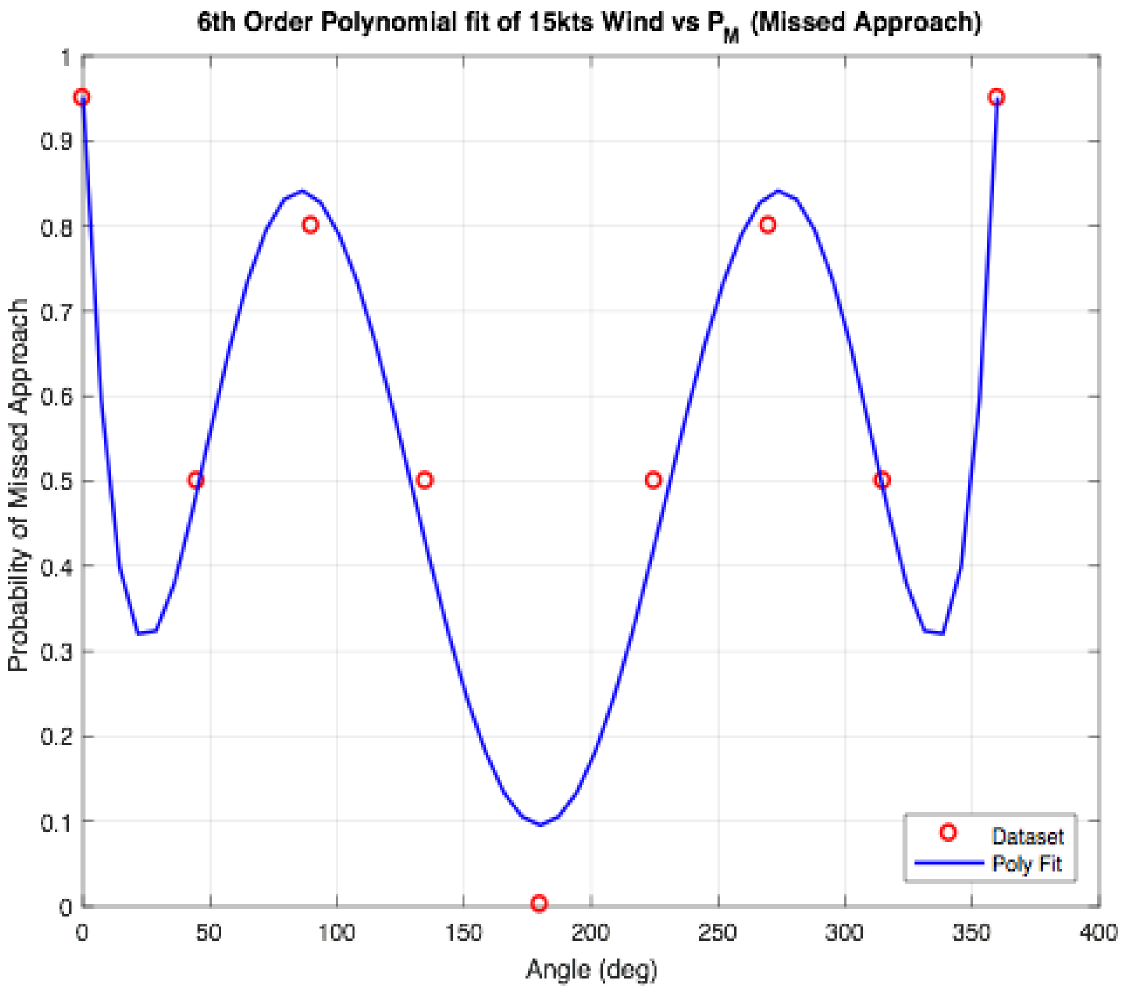
# Reconfiguration Example

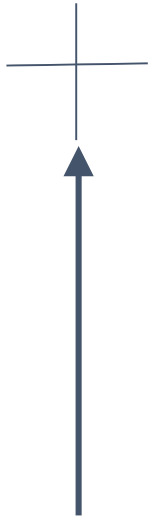




# MDP Elements for Runway Reconfiguration

- 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 →





0 degrees, positive CW

# 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

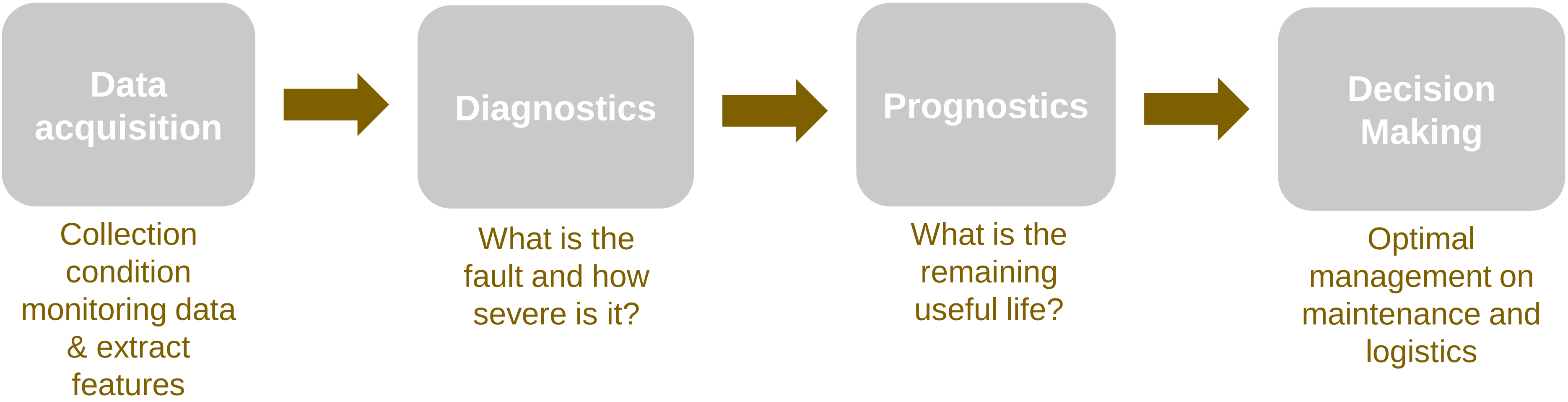
# SHM for Satellites

- ☐ **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



**Data acquisition**

Collection condition monitoring data & extract features

**Diagnostics**

What is the fault and how severe is it?

**Prognostics**

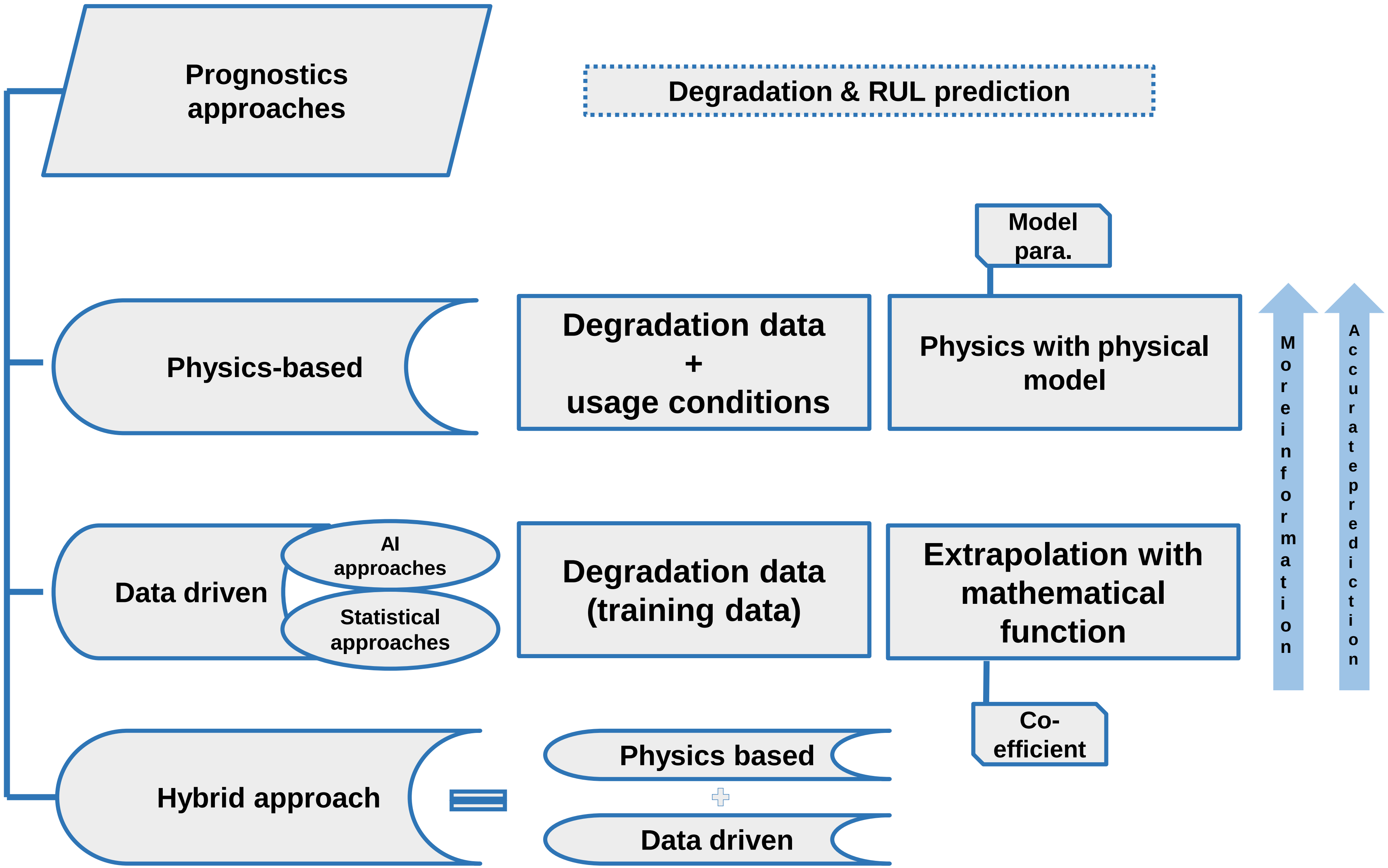
What is the remaining useful life?

**Decision Making**

Optimal management on maintenance and logistics

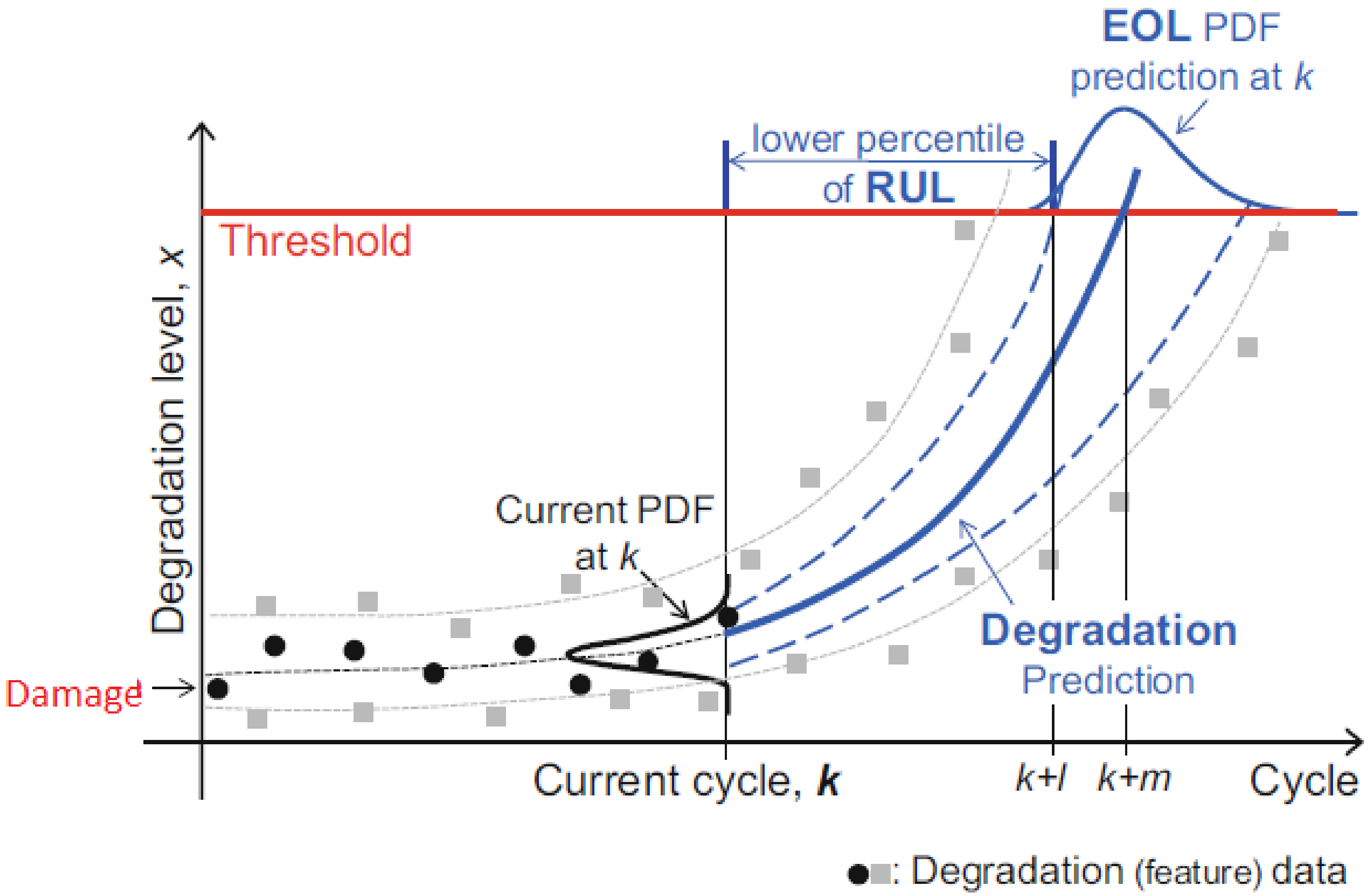
- **Prognostics** provides the decision maker an early warning about the expected time to system/subsystem/component failure

# 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



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

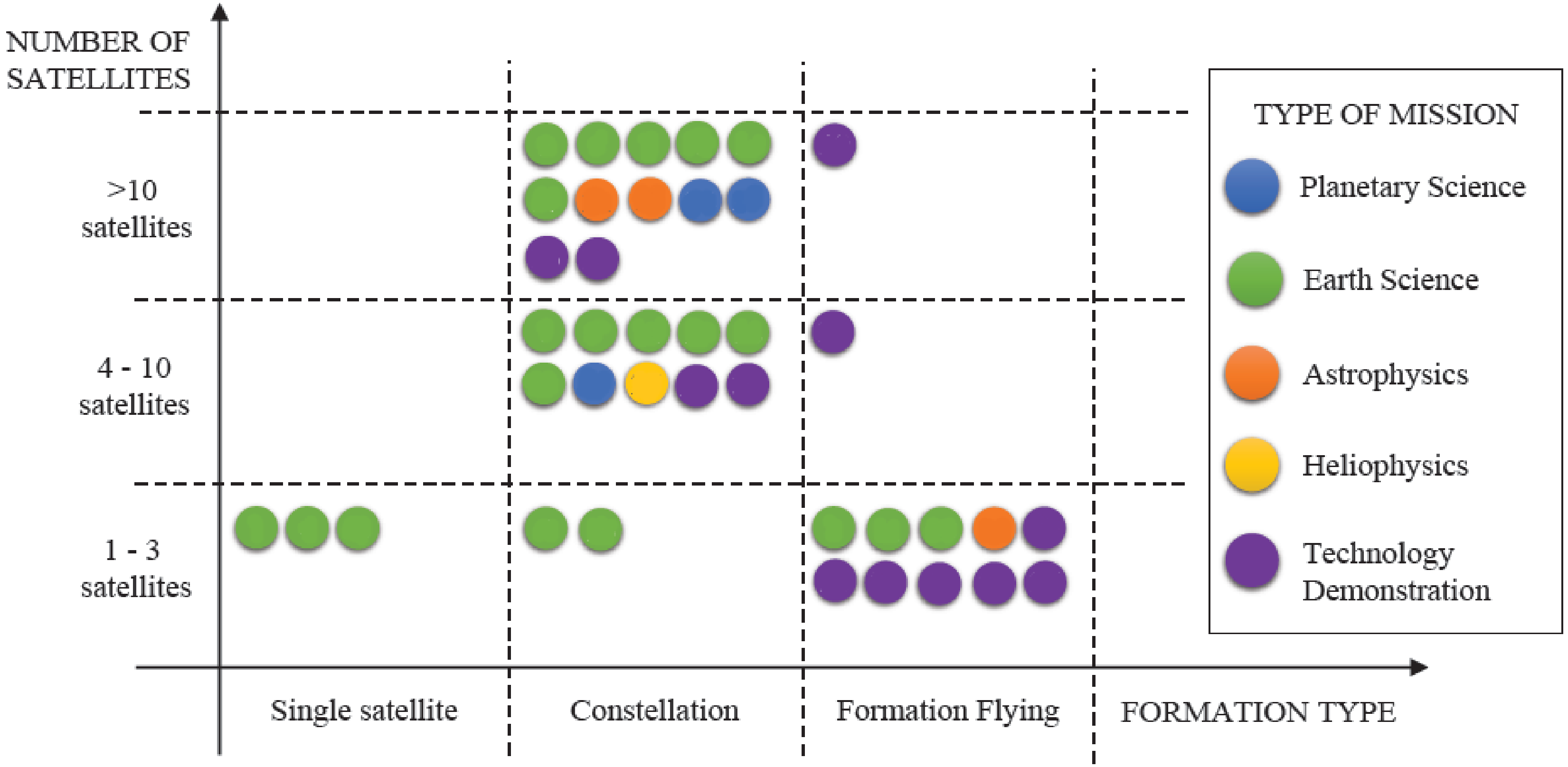
# RUL Methodologies

- Remaining Useful Life Estimation Methodology
  - Model Based
    - Physical Model
    - Cumulative Damage
    - Hazard Rate Proportional Hazard Rate
    - Nonlinear Dynamics
  - Data Driven
    - Neural Network
    - Support Vector Machine
    - Bayesian Network
    - Hidden(Markov, semi markov)
  - Hybrid
    - Statistical Model
    - Fourier Transform with Neural Network
    - Statistical Model with Neural Network
    - Fuzzy Logic with Neural Network
    - Wavelet Transform Analysis with Statistical Model
    - Dynamic Wavelet with Neural Network

*1. .Ahmadzadeh, F., & Lundberg, J. (2014). Remaining useful life estimation. International Journal of System Assurance Engineering and Management, 5(4), 461-474.*

# 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.

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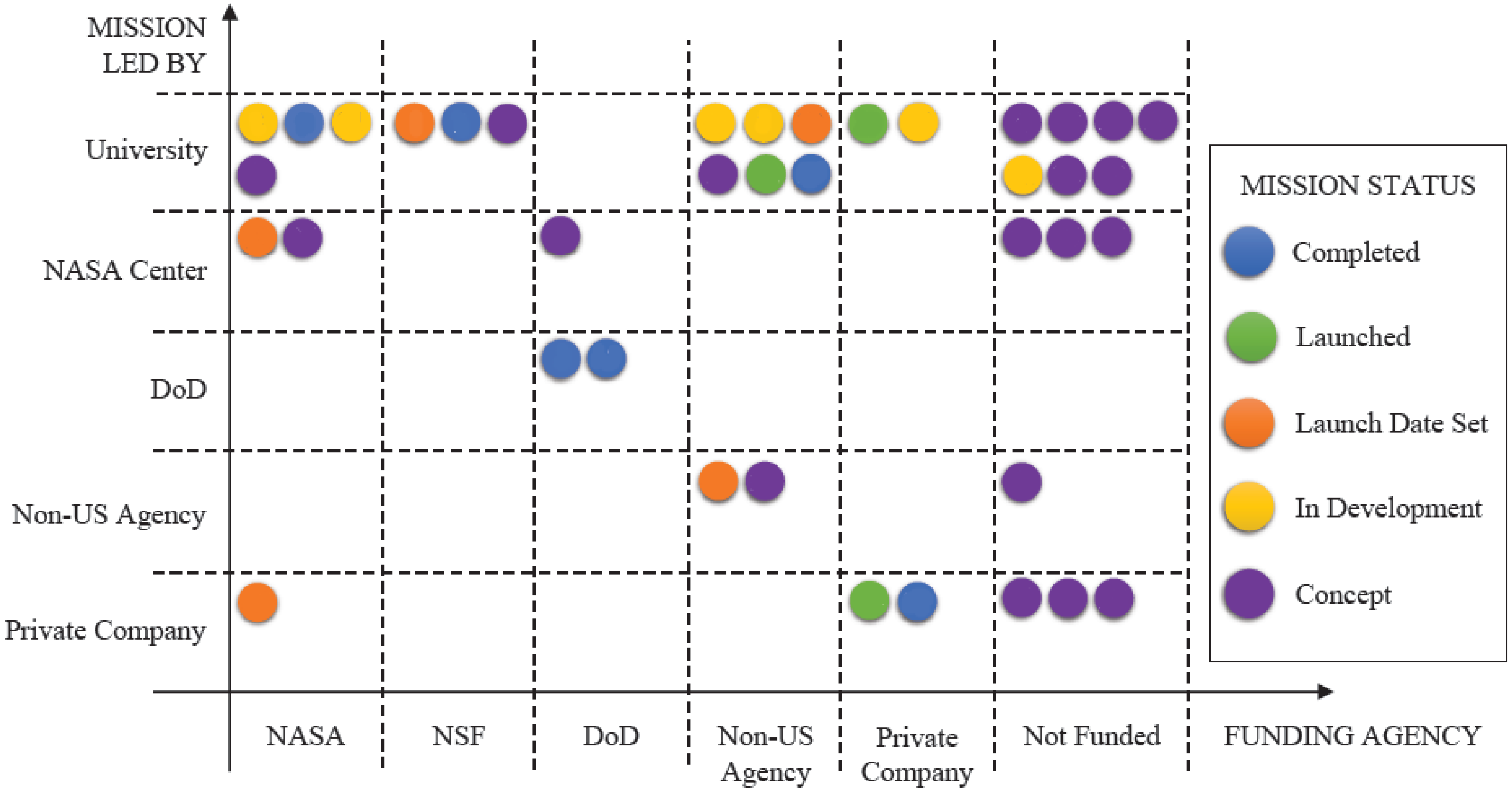
❑ Categorization of thirty-nine multi-satellite missions based on their mission status, leading organization and funding source



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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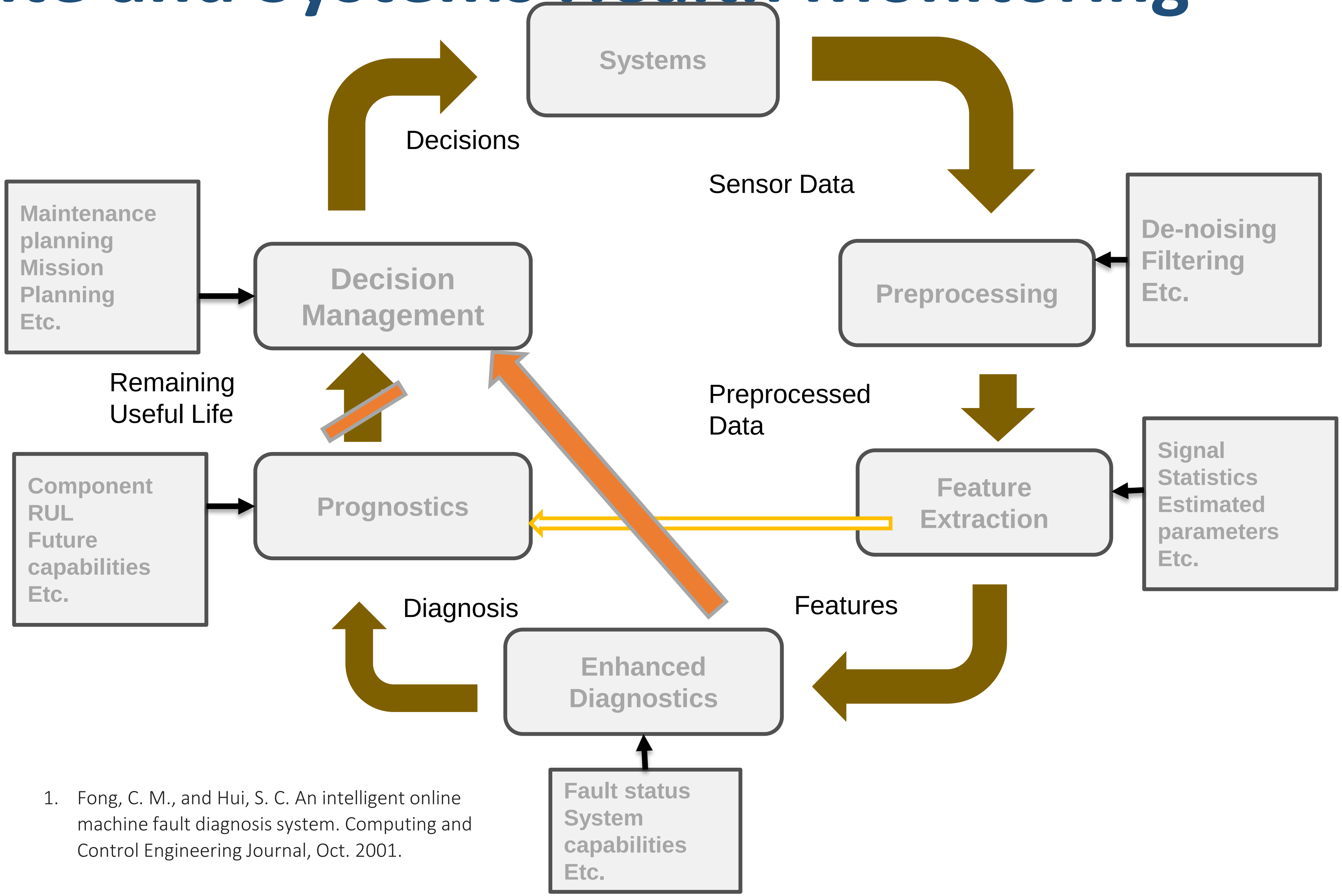
# Goals for Satellite Missions

- 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

1. Vassev, E., & Hinchey, M. (2014). *Autonomy Requirements Engineering for Space Missions*: Springer.

# Satellite and Systems Health Monitoring



Systems

Sensor Data

Preprocessing

De-noising
Filtering
Etc.

Preprocessed
Data

Feature
Extraction

Signal
Statistics
Estimated
parameters
Etc.

Features

Enhanced
Diagnostics

Fault status
System
capabilities
Etc.

Diagnosis

Prognostics

Component
RUL
Future
capabilities
Etc.

Remaining
Useful Life

Decision
Management

Maintenance
planning
Mission
Planning
Etc.

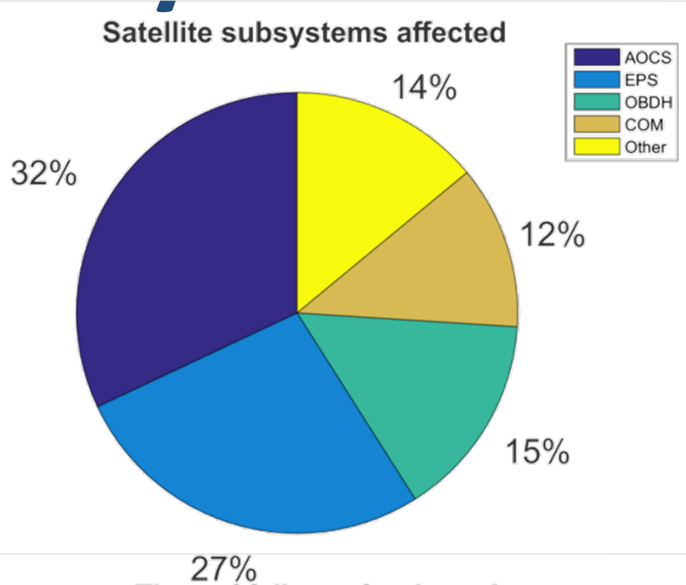
Decisions

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

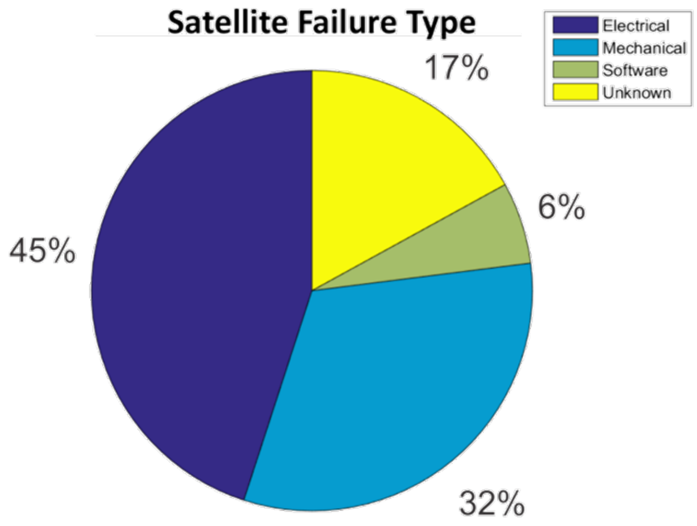
# Satellite Subsystems

- 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)

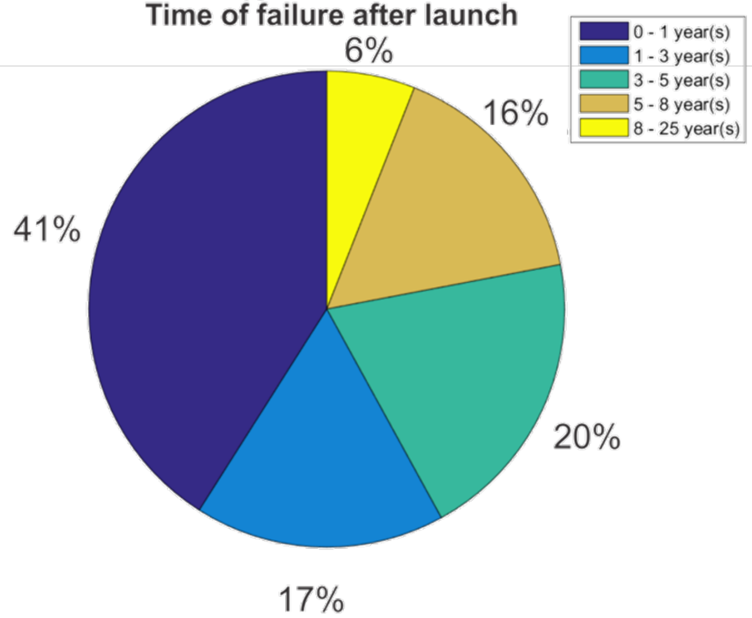
# Satellite Subsystems Anomalies and Failures



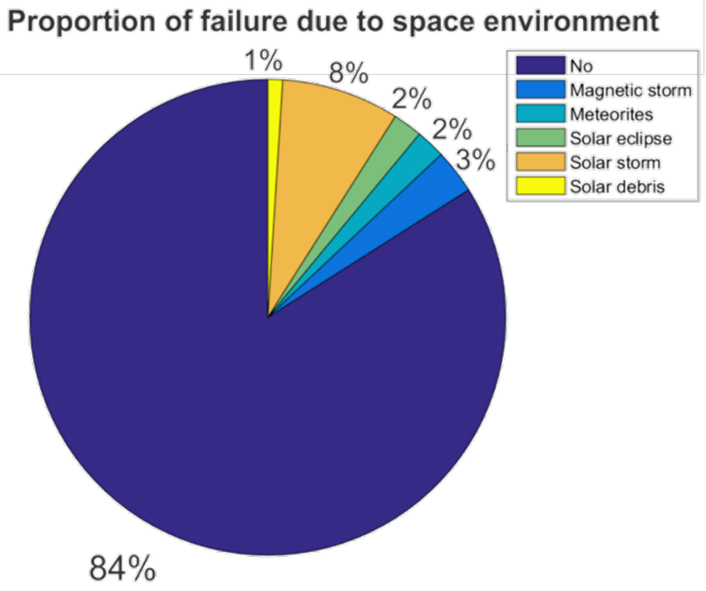
Satellite subsystems affected



Satellite Failure Type



Time of failure after launch



Proportion of failure due to space environment

1. Tafazoli, M. (2009). A study of on-orbit spacecraft failures. *Acta Astronautica, 64*(2), 195-205. .

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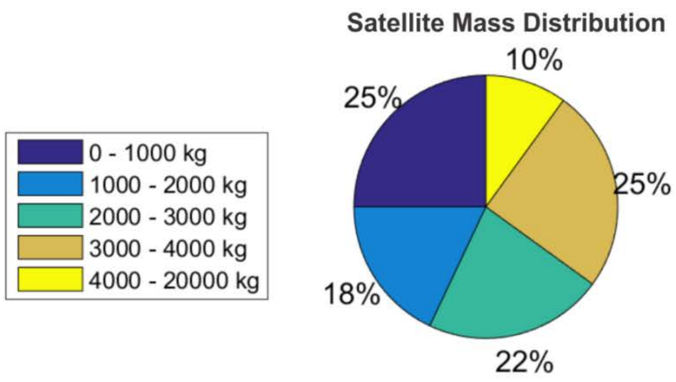

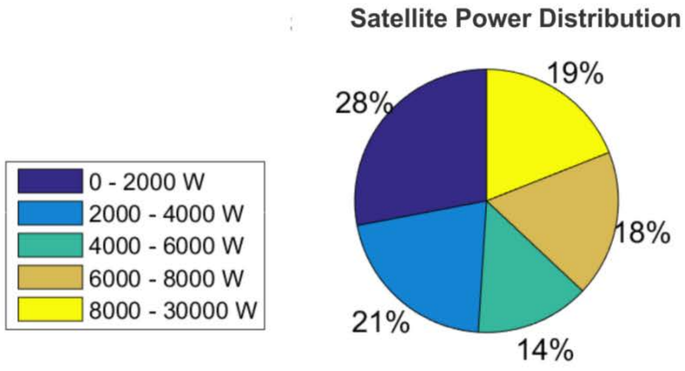

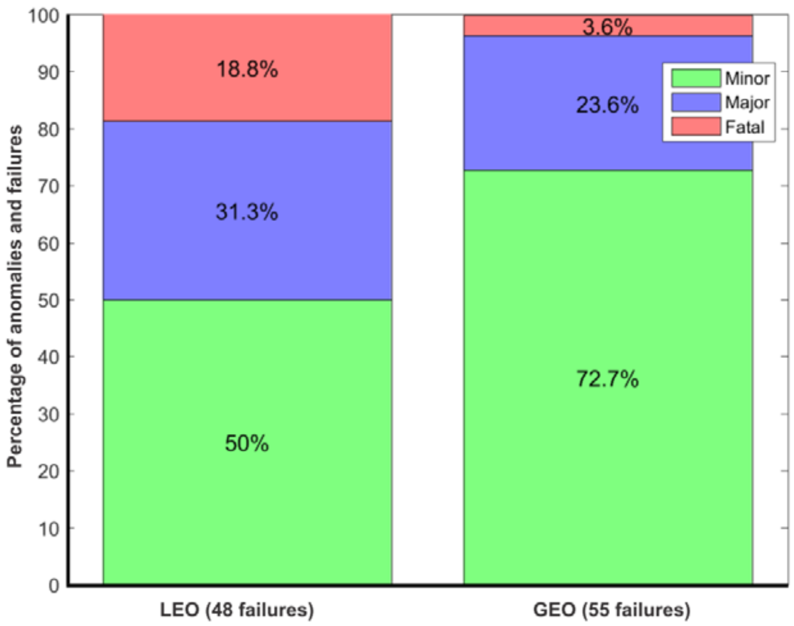

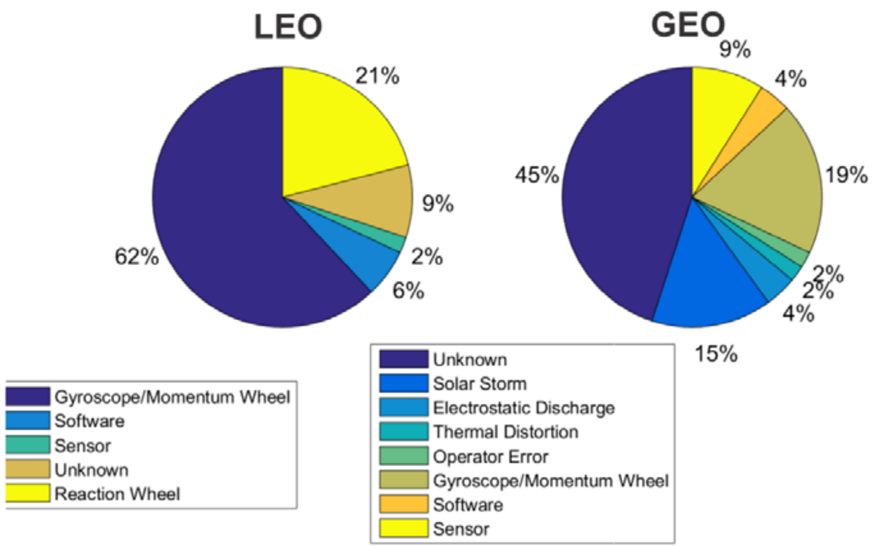

1. Wayer, J. K., Castet, J. F., & Saleh, J. H. (2013). Spacecraft attitude control subsystem: Reliability, multi-state analyses, and comparative failure behavior in LEO and GEO. *Acta Astronautica*, *85*, 83-92.

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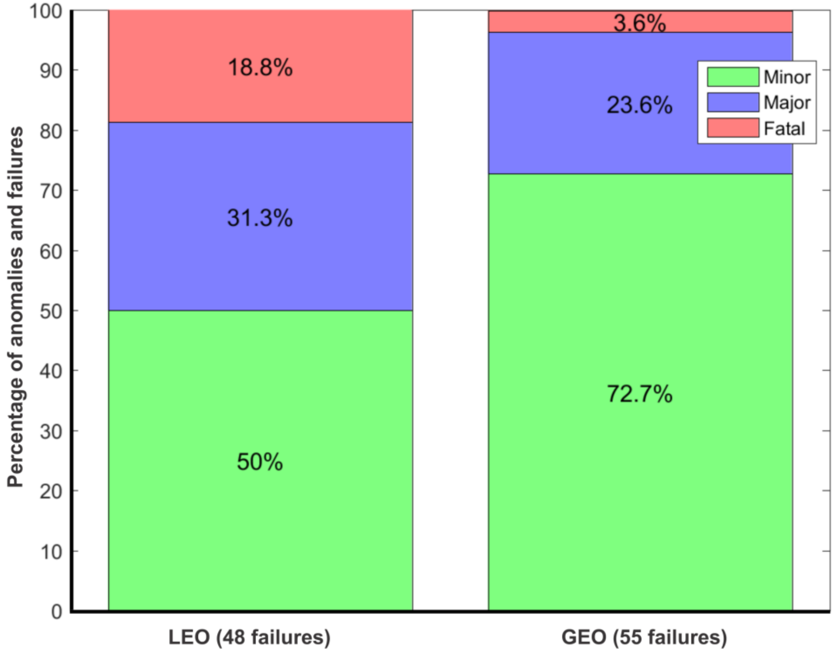

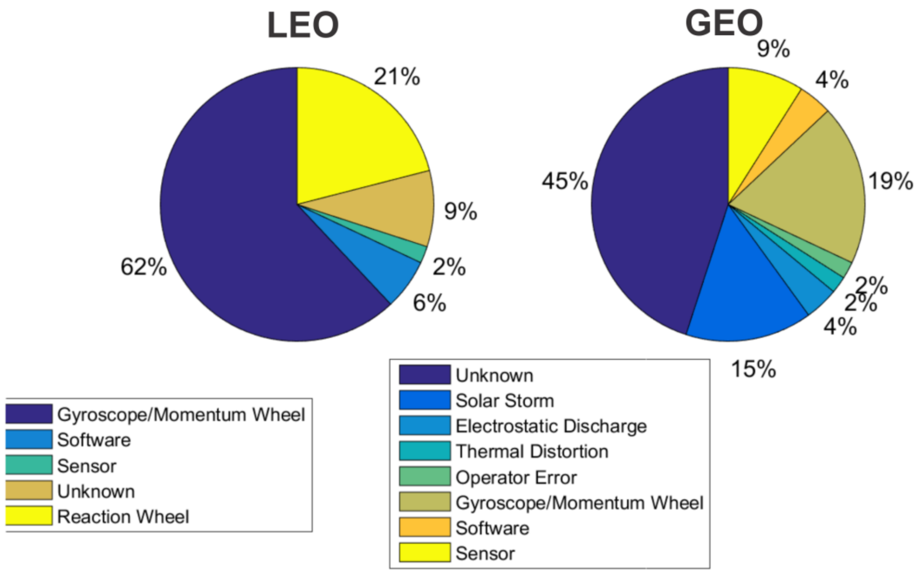

1. Wayer, J. K., Castet, J. F., & Saleh, J. H. (2013). Spacecraft attitude control subsystem: Reliability, multi-state analyses, and comparative failure behavior in LEO and GEO. *Acta Astronautica*, *85*, 83-92.

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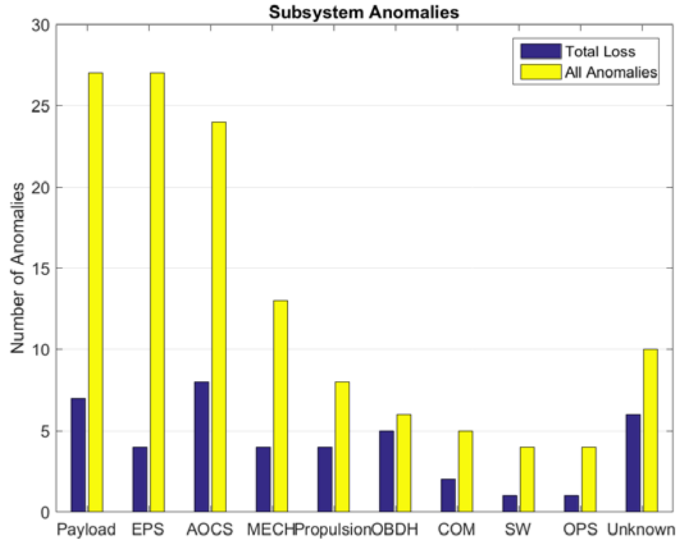
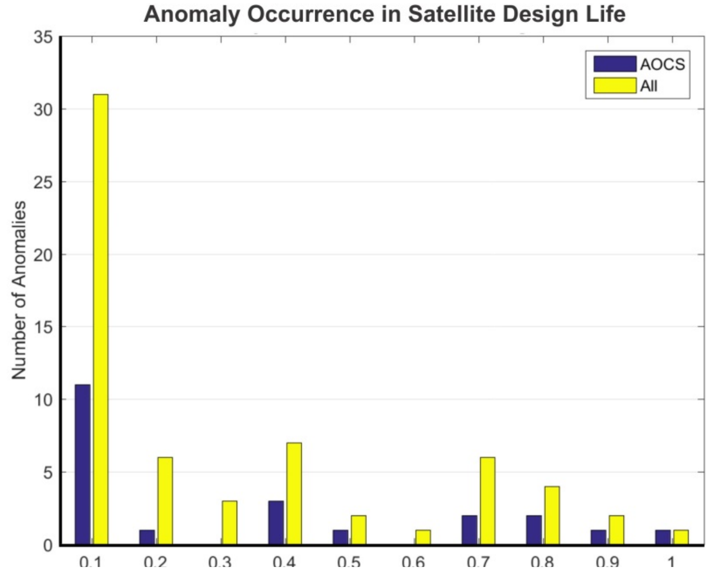
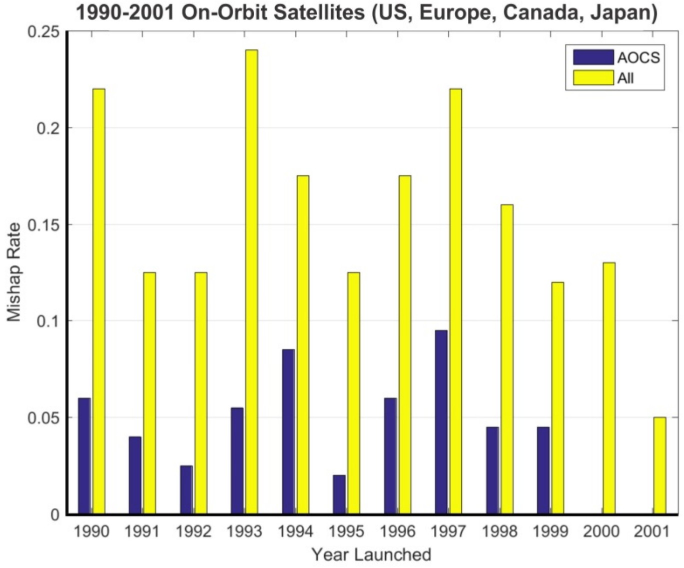
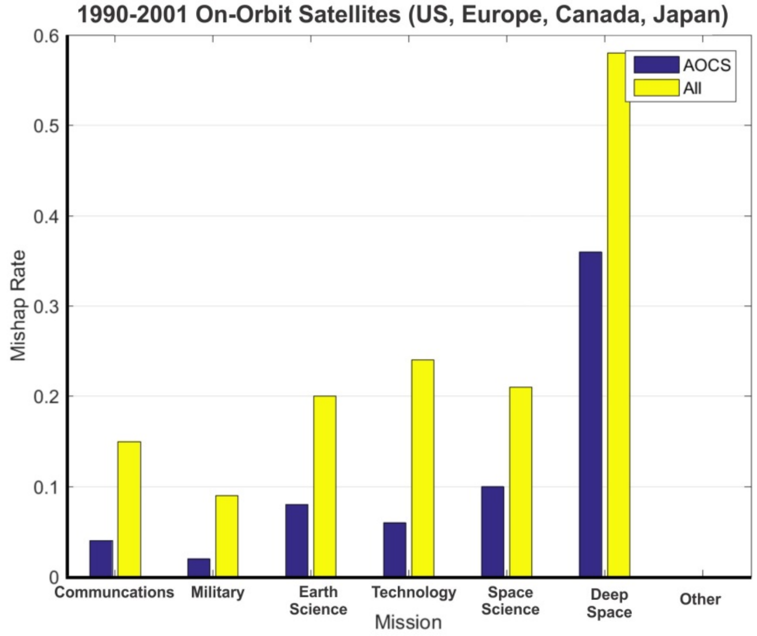




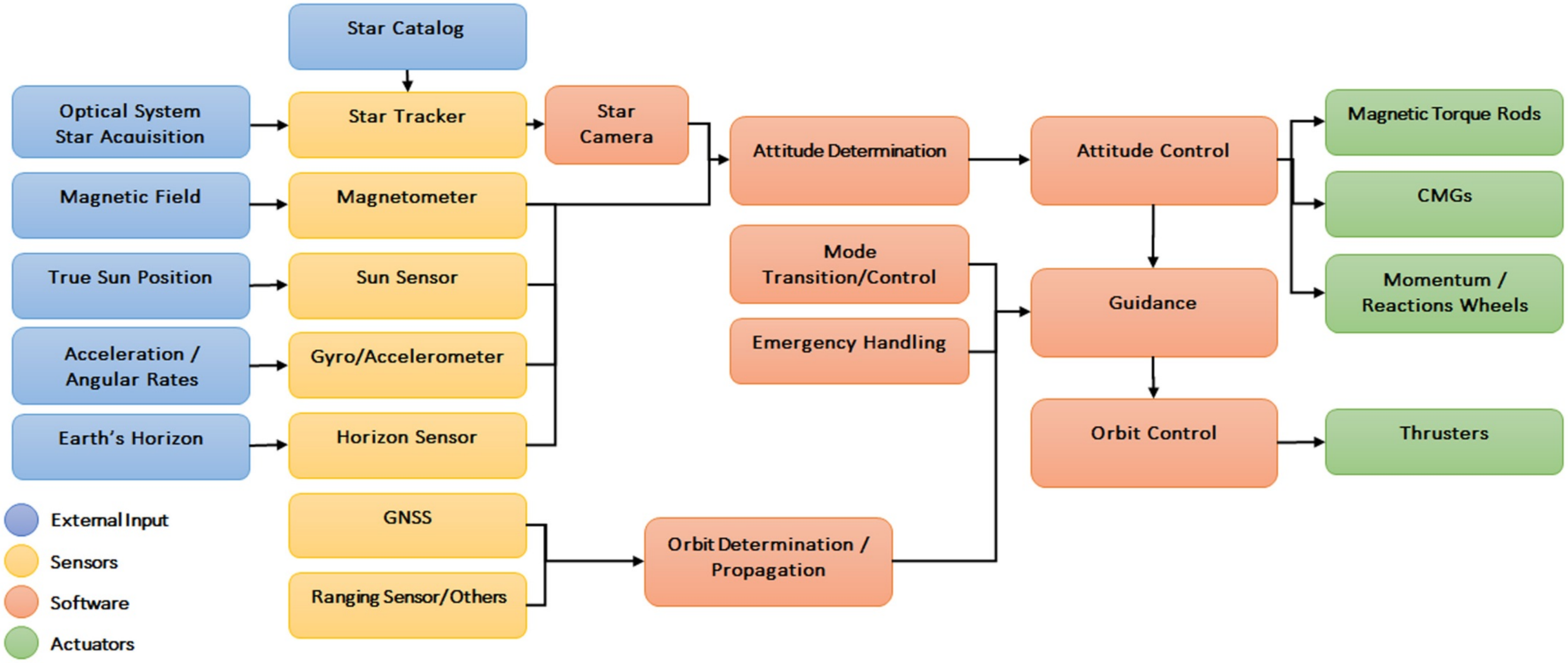




1. Robertson, B., & Stoneking, E. (2003). Satellite GN & C anomaly trends. *Advances in the Astronautical Sciences, 113*, 531-542.

# SHM for AOCS Subsystem

# Attitude and Orbit Control



Star Catalog

Optical System Star Acquisition

Star Tracker

Star Camera

Magnetic Field

Magnetometer

True Sun Position

Sun Sensor

Acceleration / Angular Rates

Gyro/Accelerometer

Earth’s Horizon

Horizon Sensor

GNSS

Ranging Sensor/Others

Attitude Determination

Mode Transition/Control

Emergency Handling

Orbit Determination / Propagation

Attitude Control

Guidance

Orbit Control

Magnetic Torque Rods

CMGs

Momentum / Reactions Wheels

Thrusters

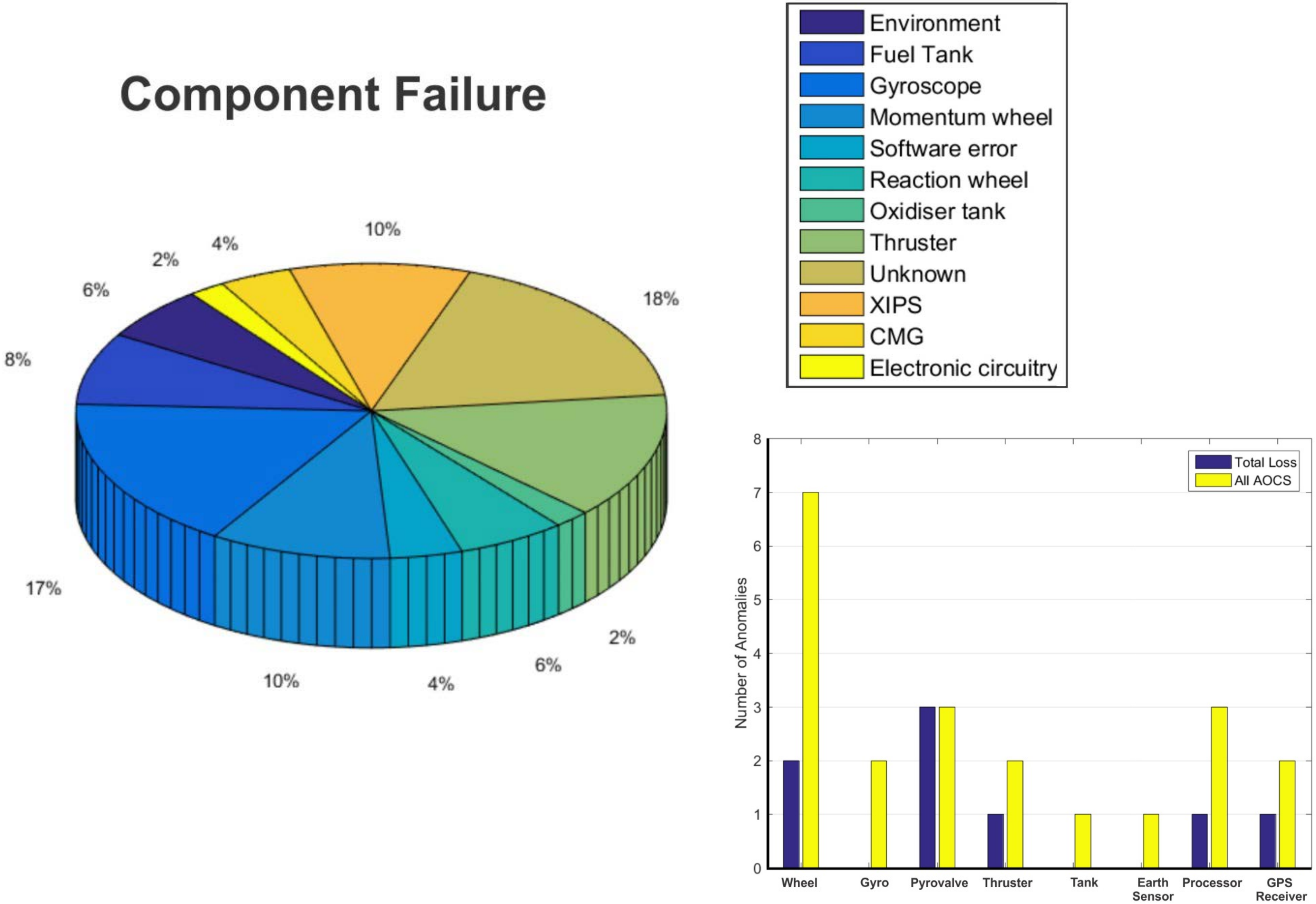
🔵 External Input

🟡 Sensors

🟠 Software

🟢 Actuators

continued



1. Tafazoli, M. (2009). A study of on-orbit spacecraft failures. *Acta Astronautica, 6*
2. Robertson, B., & Stoneking, E. (2003). Satellite GN & C anomaly trends. *Advances in the Astronautical Sciences, 113*, 531-542.

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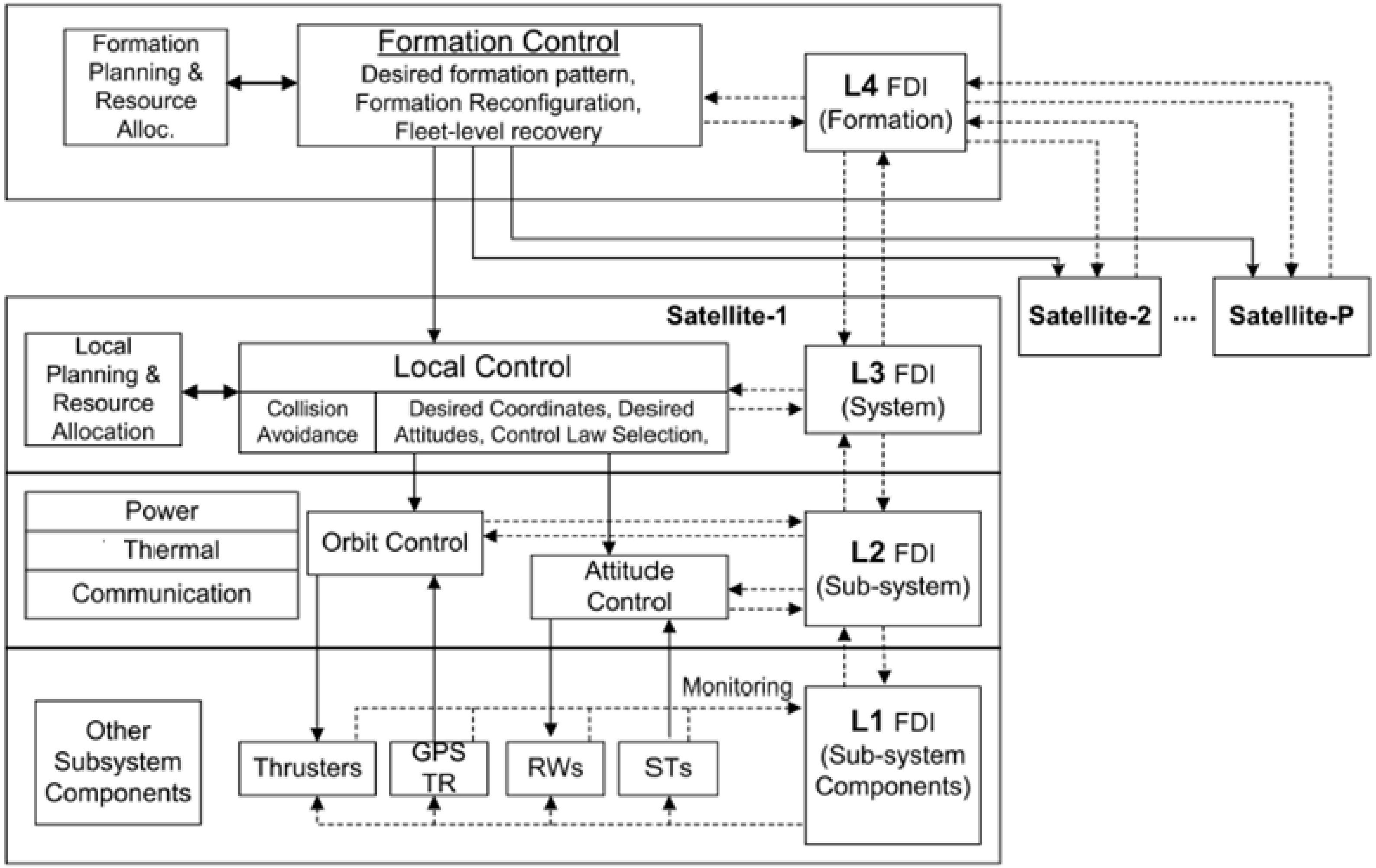
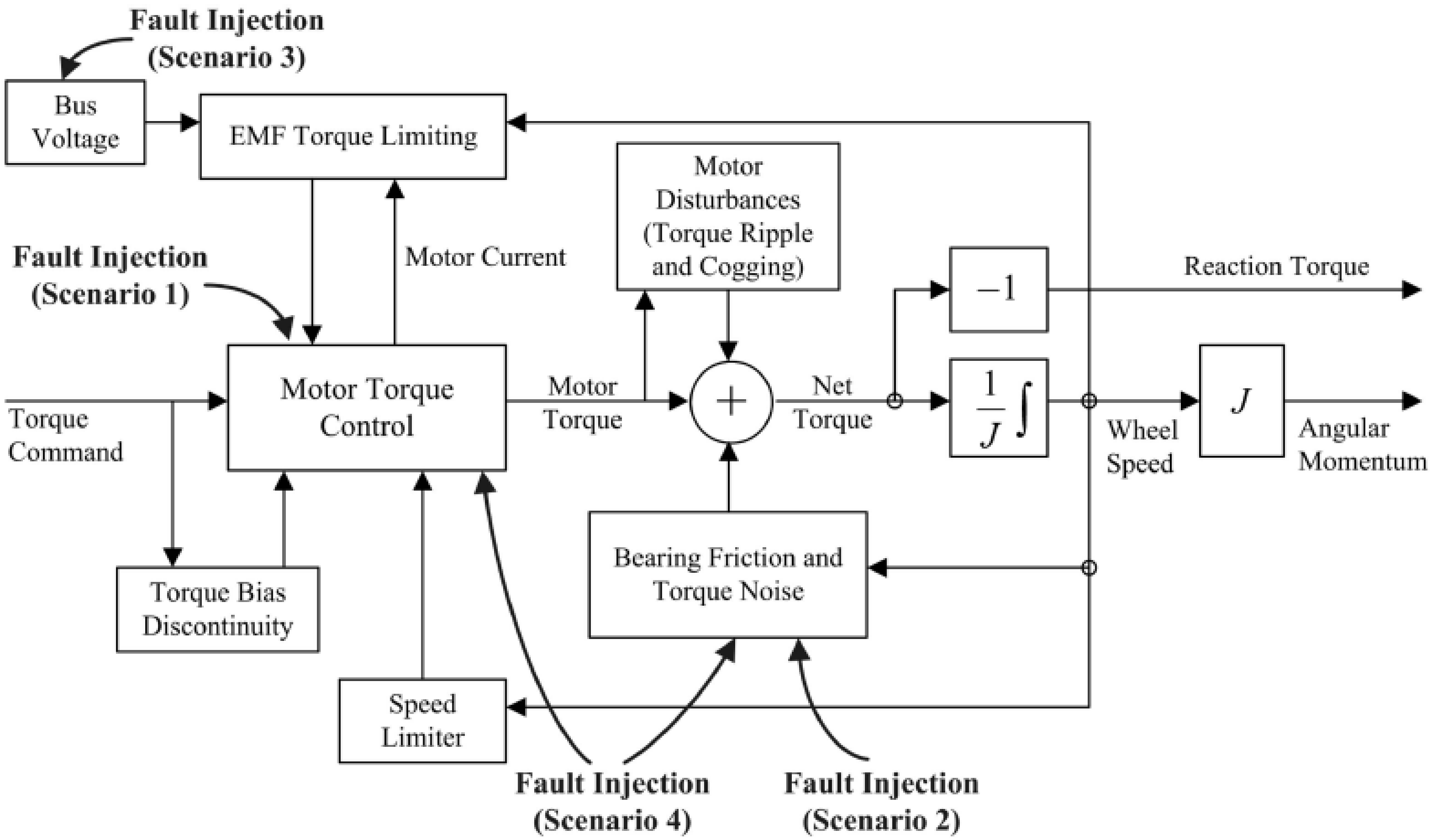


Proposed FDI framework for a multi-platform formation flight space missions.

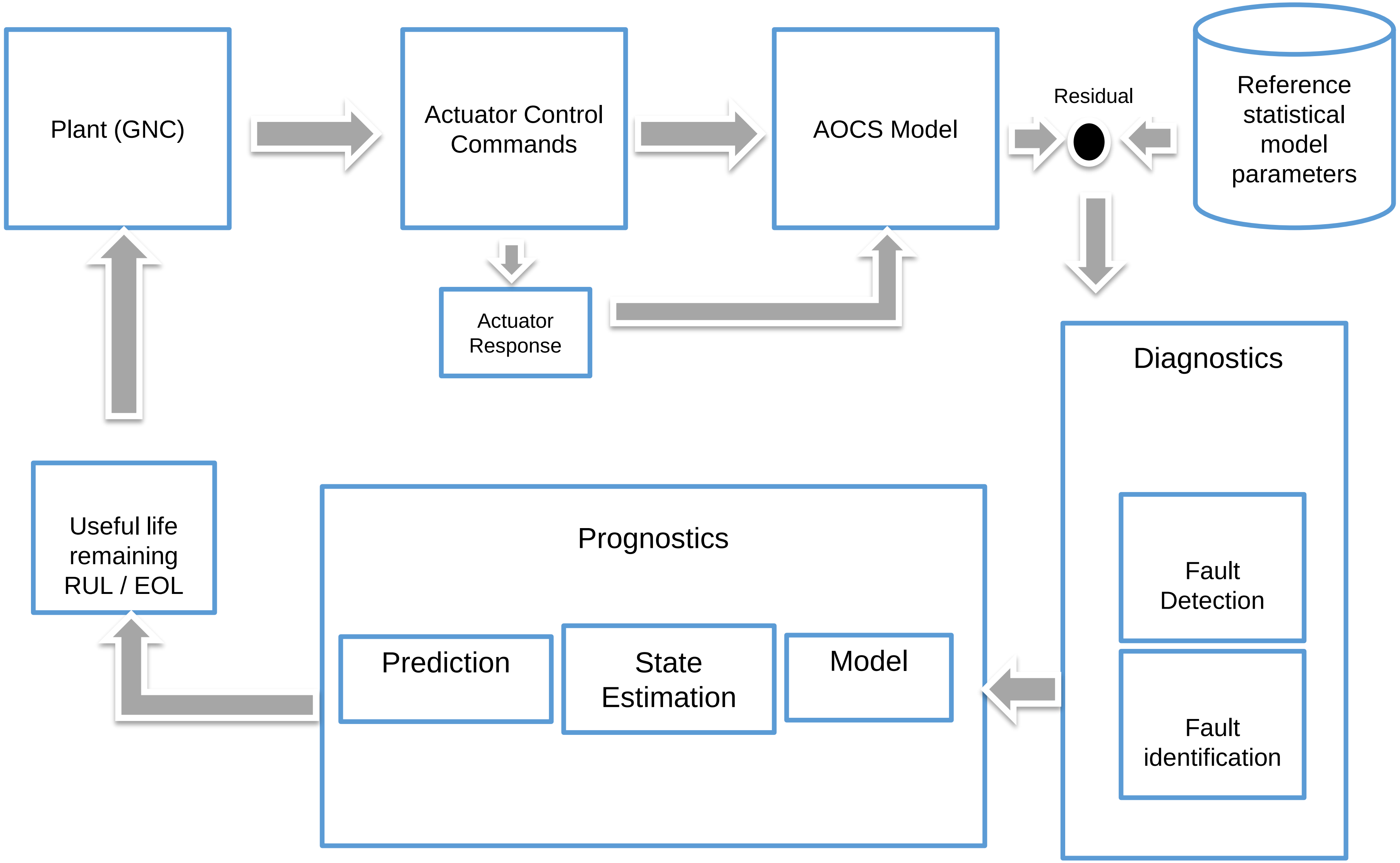
1. Barua, A., & Khorasani, K. (2011). Hierarchical fault diagnosis and health monitoring in satellites formation flight. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 41*(2), 223-239.

# 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


Fault Injection (Scenario 3)
Bus Voltage
EMF Torque Limiting
Motor Current
Fault Injection (Scenario 1)
Motor Disturbances (Torque Ripple and Cogging)
Motor Torque Control
Torque Command
Motor Torque
+
Net Torque
−1
Reaction Torque
$\frac{1}{J}\int$
Wheel Speed
J
Angular Momentum
Torque Bias Discontinuity
Bearing Friction and Torque Noise
Speed Limiter
Fault Injection (Scenario 4)
Fault Injection (Scenario 2)

# 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

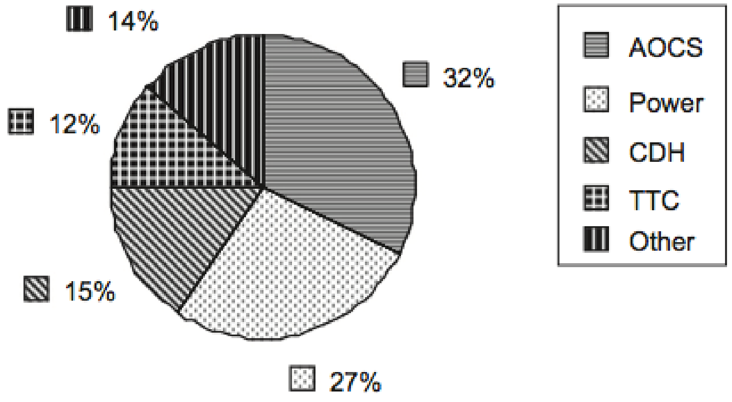


Fig. 1. Spacecraft subsystems affected.

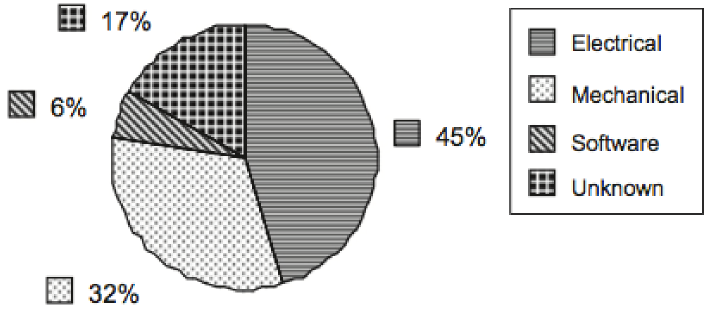


Fig. 2. Spacecraft failure type.

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

Determine component for study

Obtain modeling sources

Model nominal and faulty operation

# 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

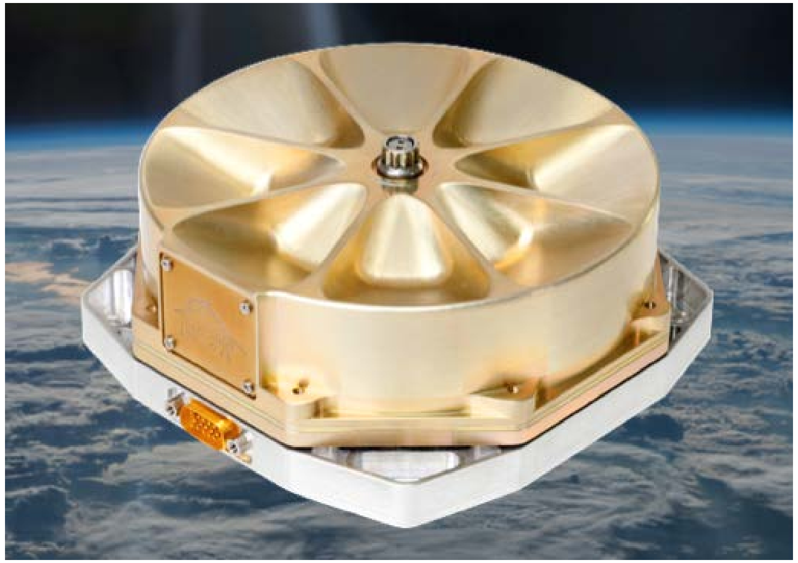
Low energy consumption

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

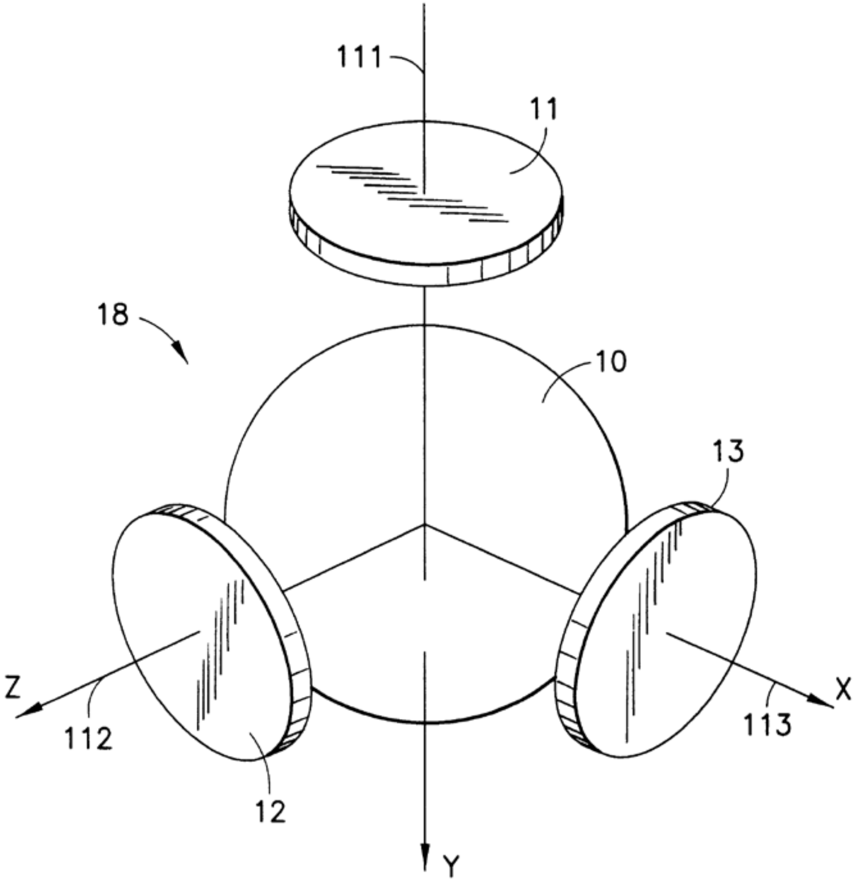


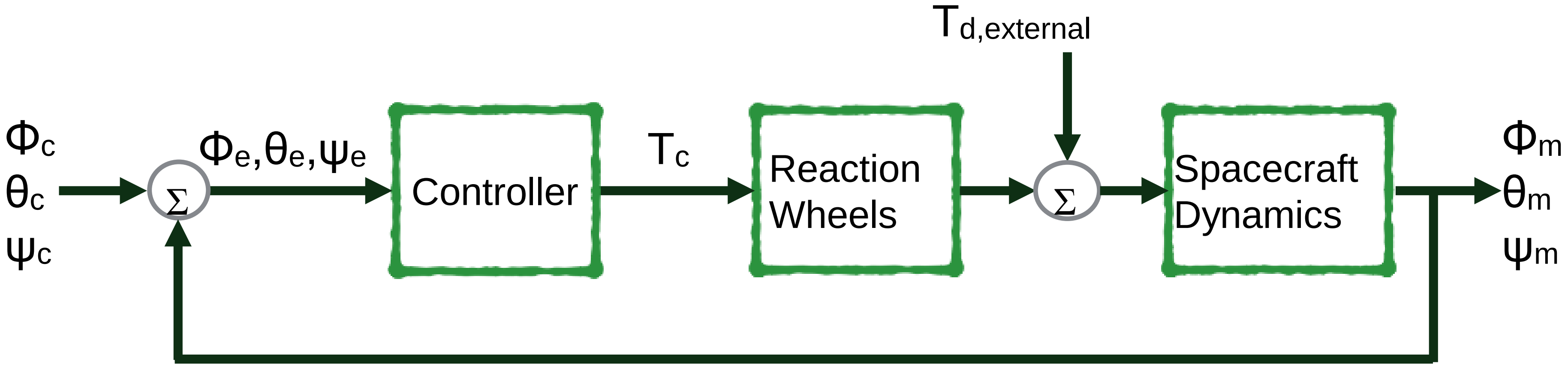
FIG.3

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

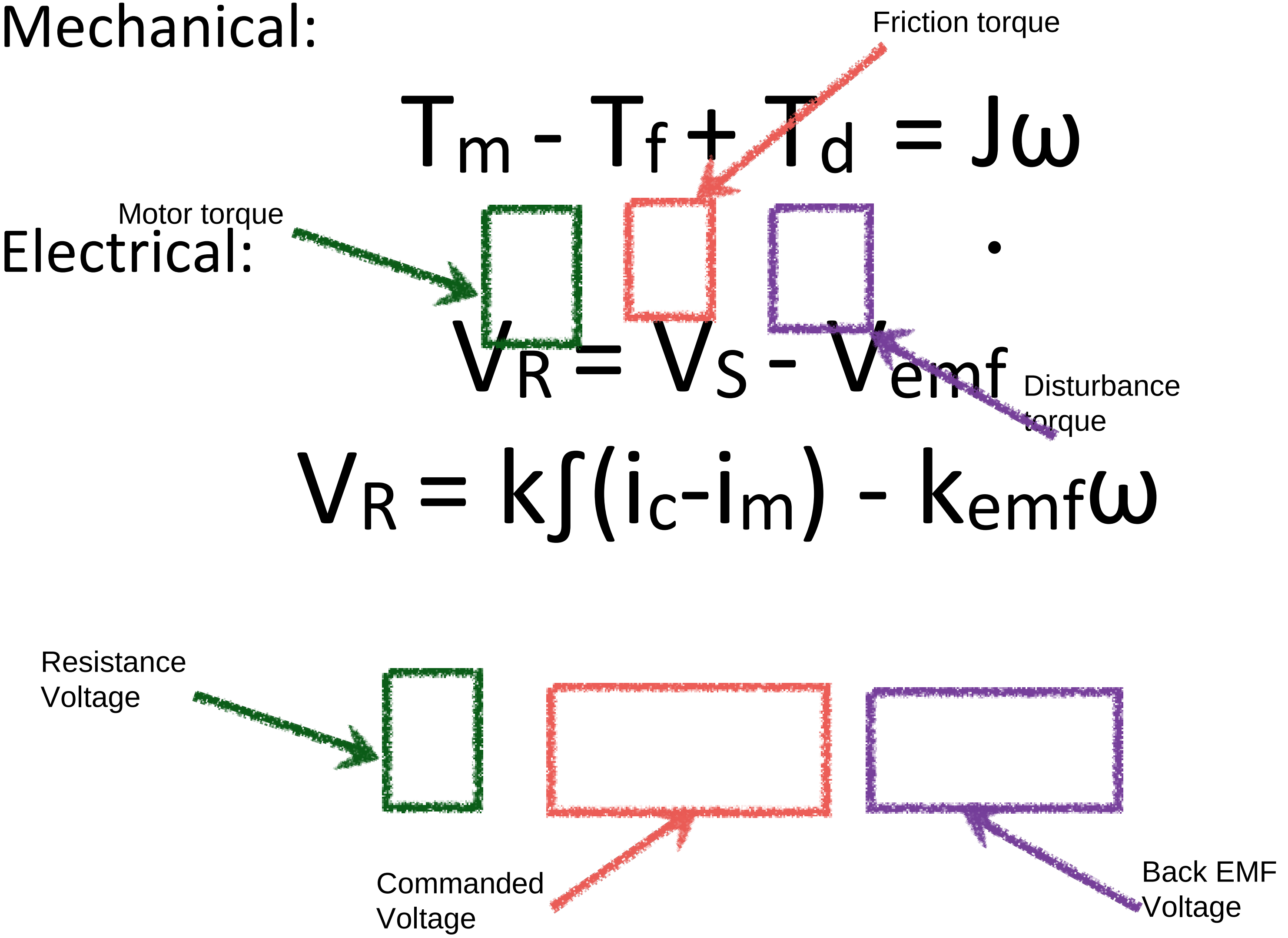
- ❑ Mechanical:

$$T_m - T_f + T_d = J\dot{\omega}$$

- ❑ Electrical:

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

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



Friction torque

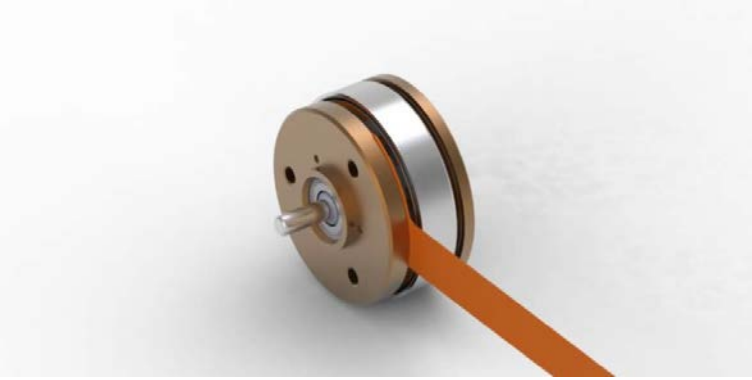
Motor torque

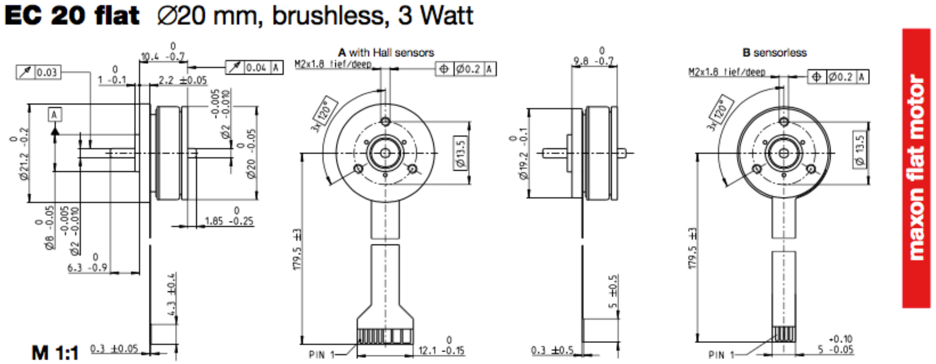
Disturbance torque

Resistance Voltage

Commanded Voltage

Back EMF Voltage





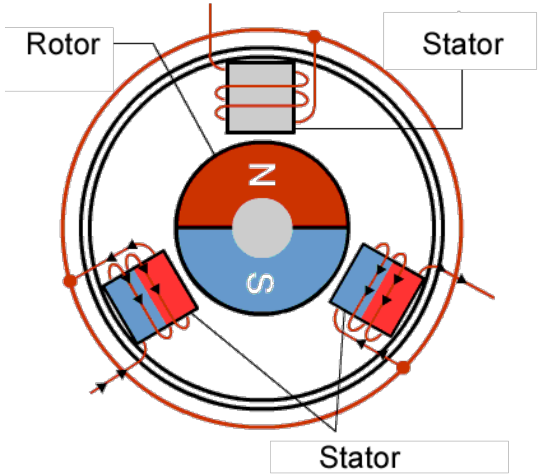
Source: Maxon Motor

| Parameter | Notation | Value |
|---|---|---|
| Torque constant | $k_m$ | 5.88 mNm/A |
| Back EMF constant | $k_{emf}$ | 5.89 mNm/A |
| Inertia of rotor | J | 1.12x10^-6 kg-m$^2$ |
| Resistance | R | 6.67 Ω |
| Number of poles | N | 8 |
| Viscous friction coefficient | b | 5.1965x10$^{-7}$ 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



Markley, F. L. & Crassidis, J.L. (2014). *Fundamentals of Spacecraft Attitude Determination and Control*, 195-203. Springer.

- **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 Rippl** e cogging torque, N is the number of

$$f_2(\omega) = B sin(3Nt\omega)$$

Khorasani, K, & Sobhani-Tehrani, E. (2009). *Fault Diagnosis of Nonlinear Systems Using a Hybrid Approach.* Springer.

# Flywheel Imbalances

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

- ❑ **Dynan** the axis of rotation of the wheel is not on the principal axis.

$$F_c = ma_c = m\frac{v^2}{r} = mr\Omega^2,$$

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

Markley, F. L. & Crassidis, J.L. (2014). *Fundamentals of Spacecraft Attitude Determination and Control*, 195-205. Springer.

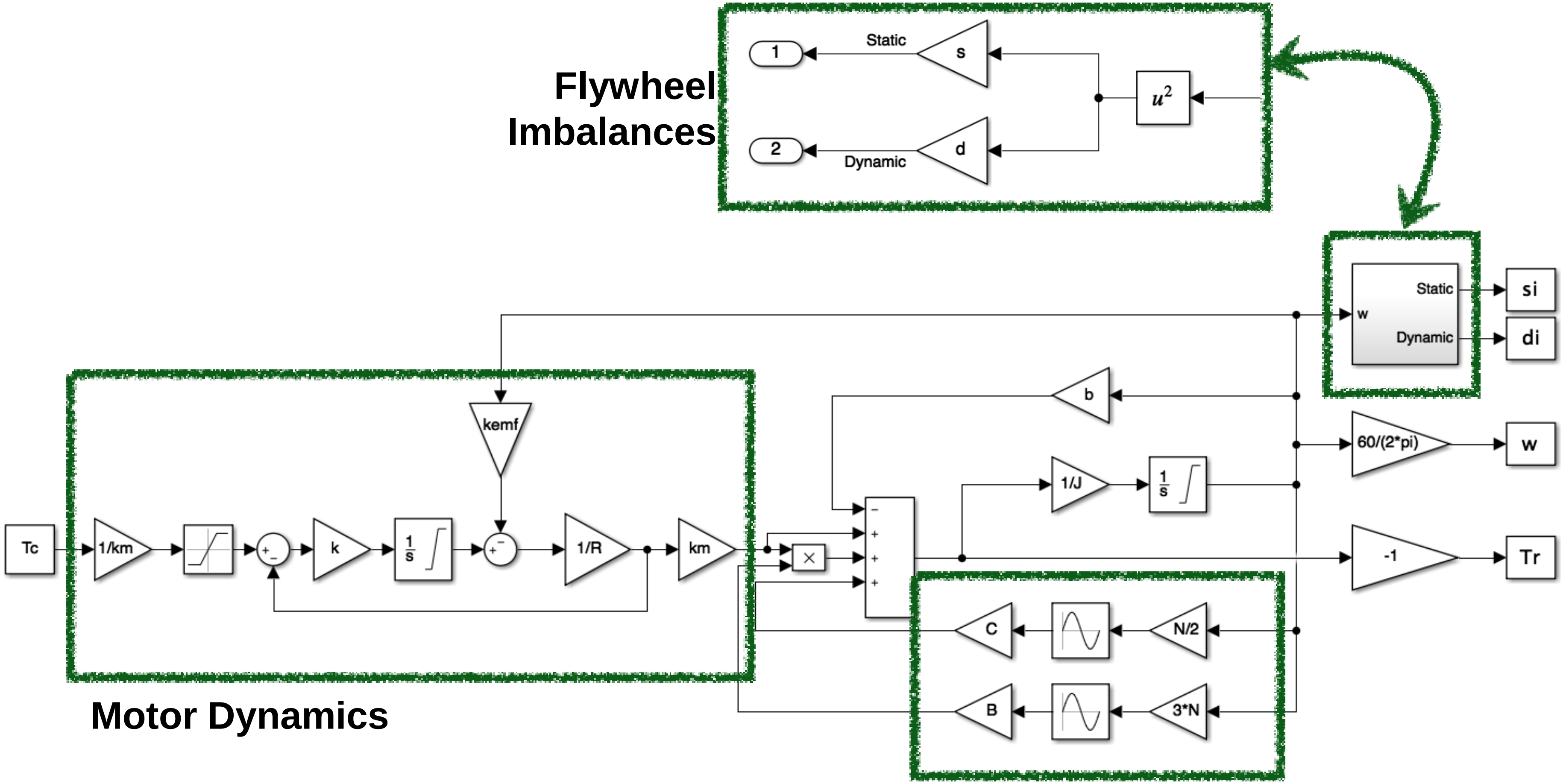
Shields, J et. al (2017). Characterization of CubeSat Reaction Wheel Assemblies. *Journal of Small Satellites, 6*(1), 565-580.

# 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

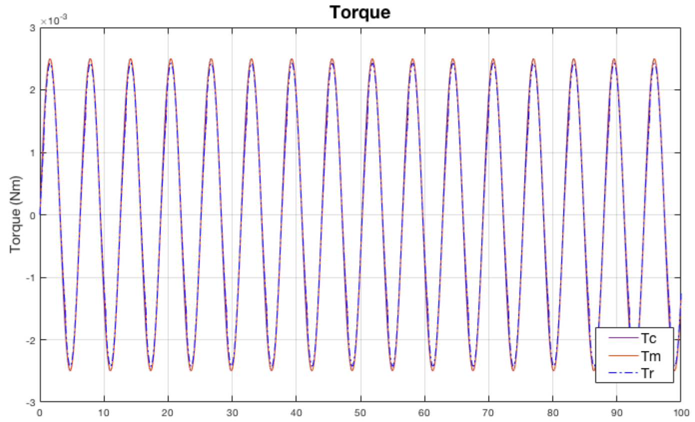


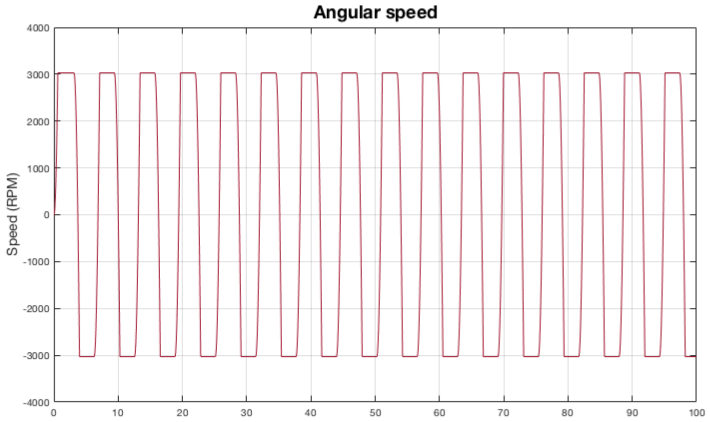
Flywheel Imbalances

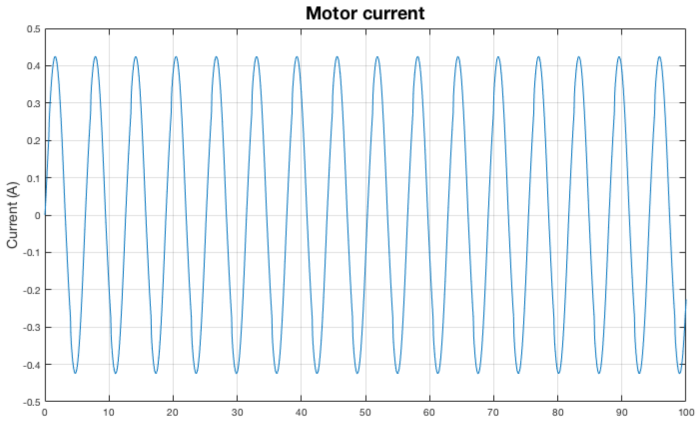
Motor Dynamics

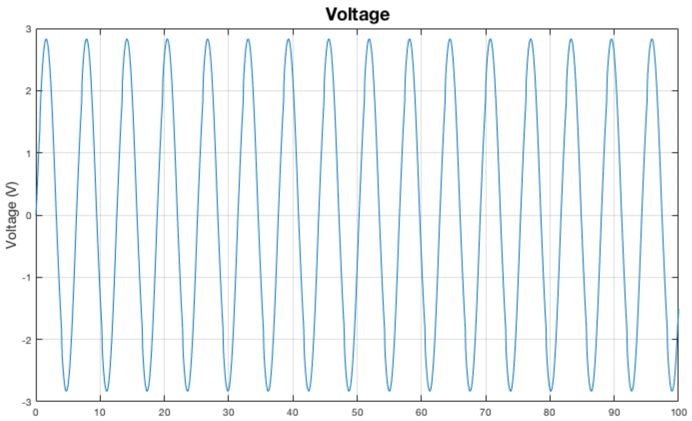
Motor disturbances

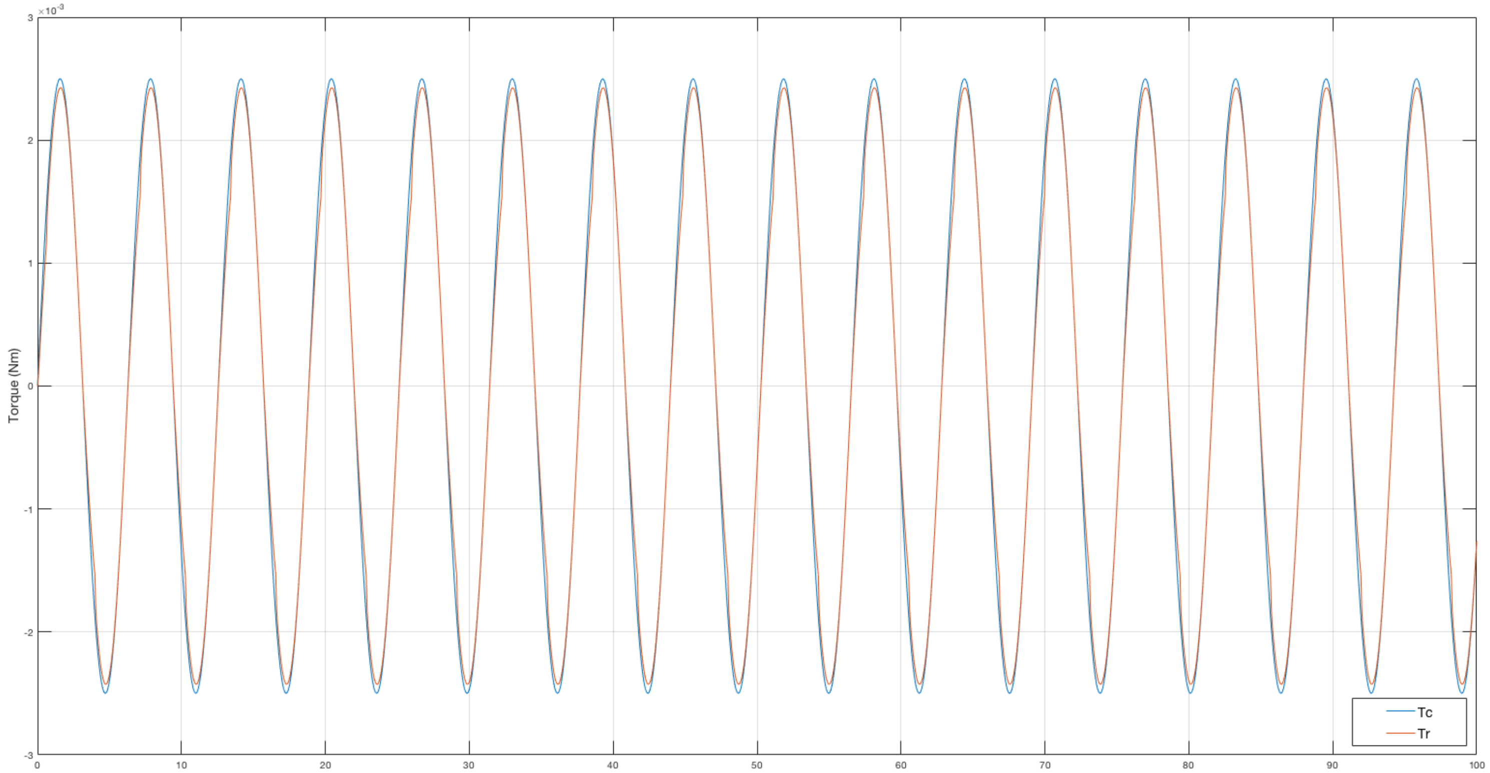
# Nominal Operation

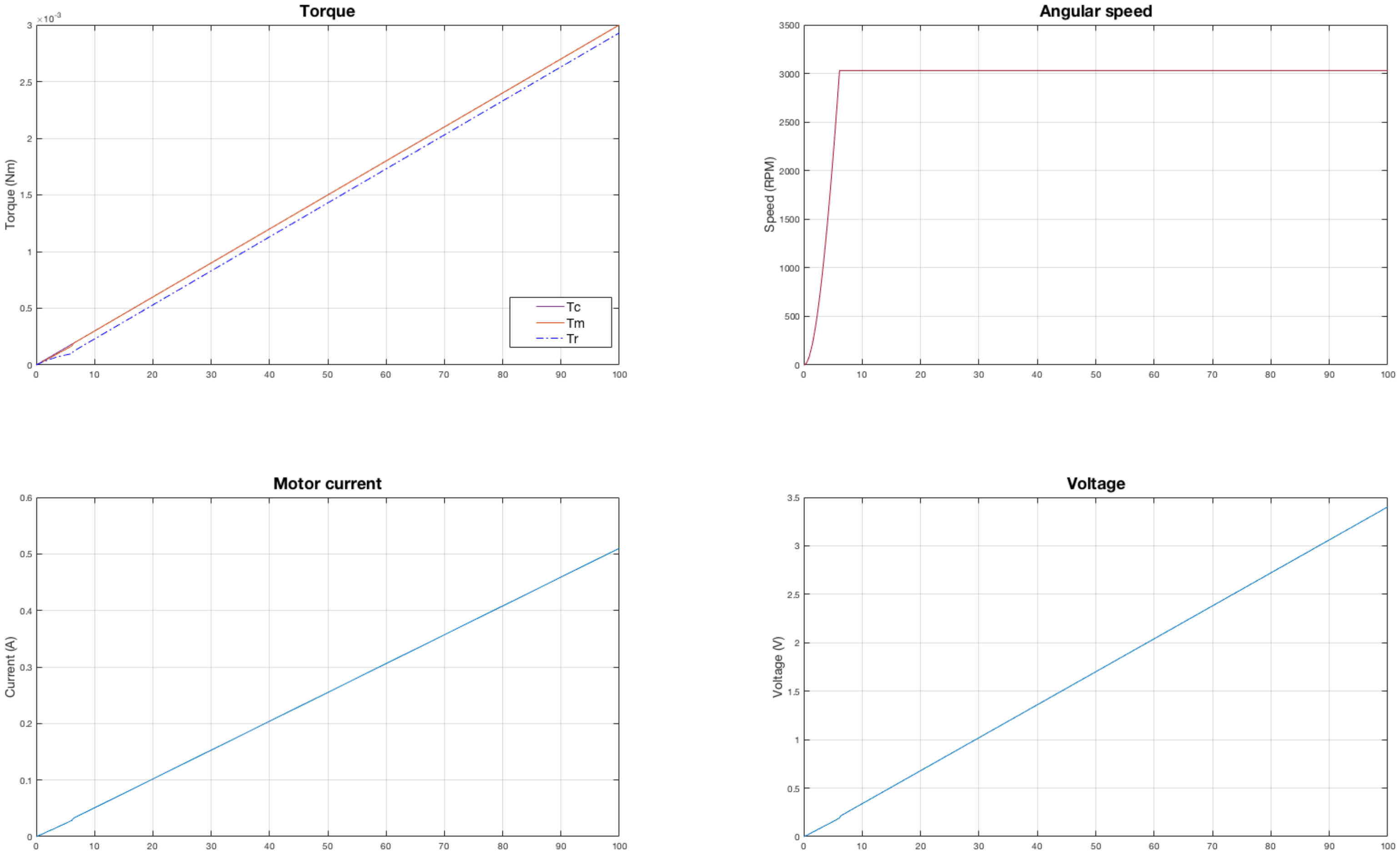

Torque
×10⁻³
3
2
1
0
-1
-2
-3
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tm
Tr

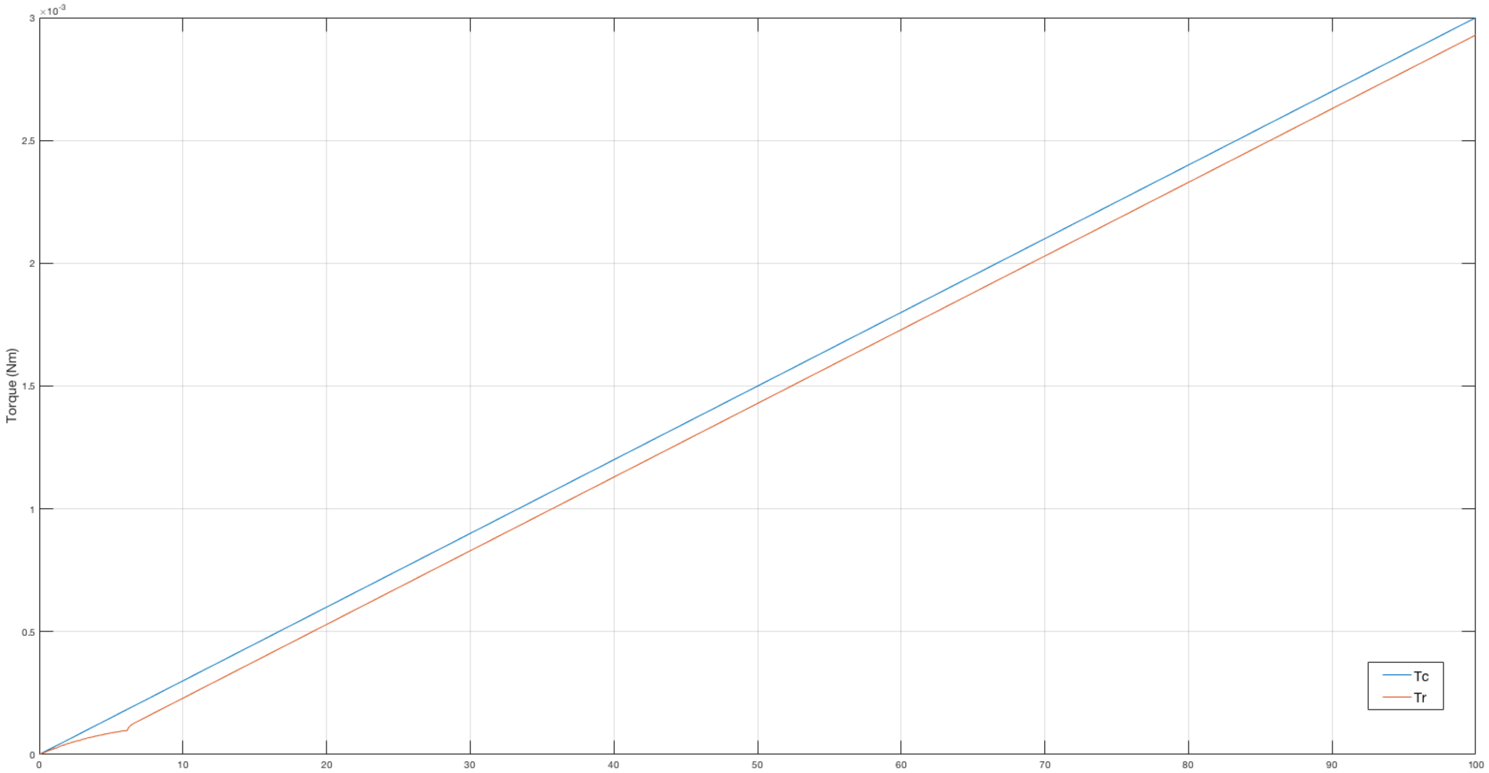

Angular speed
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
Speed (RPM)
0
10
20
30
40
50
60
70
80
90
100

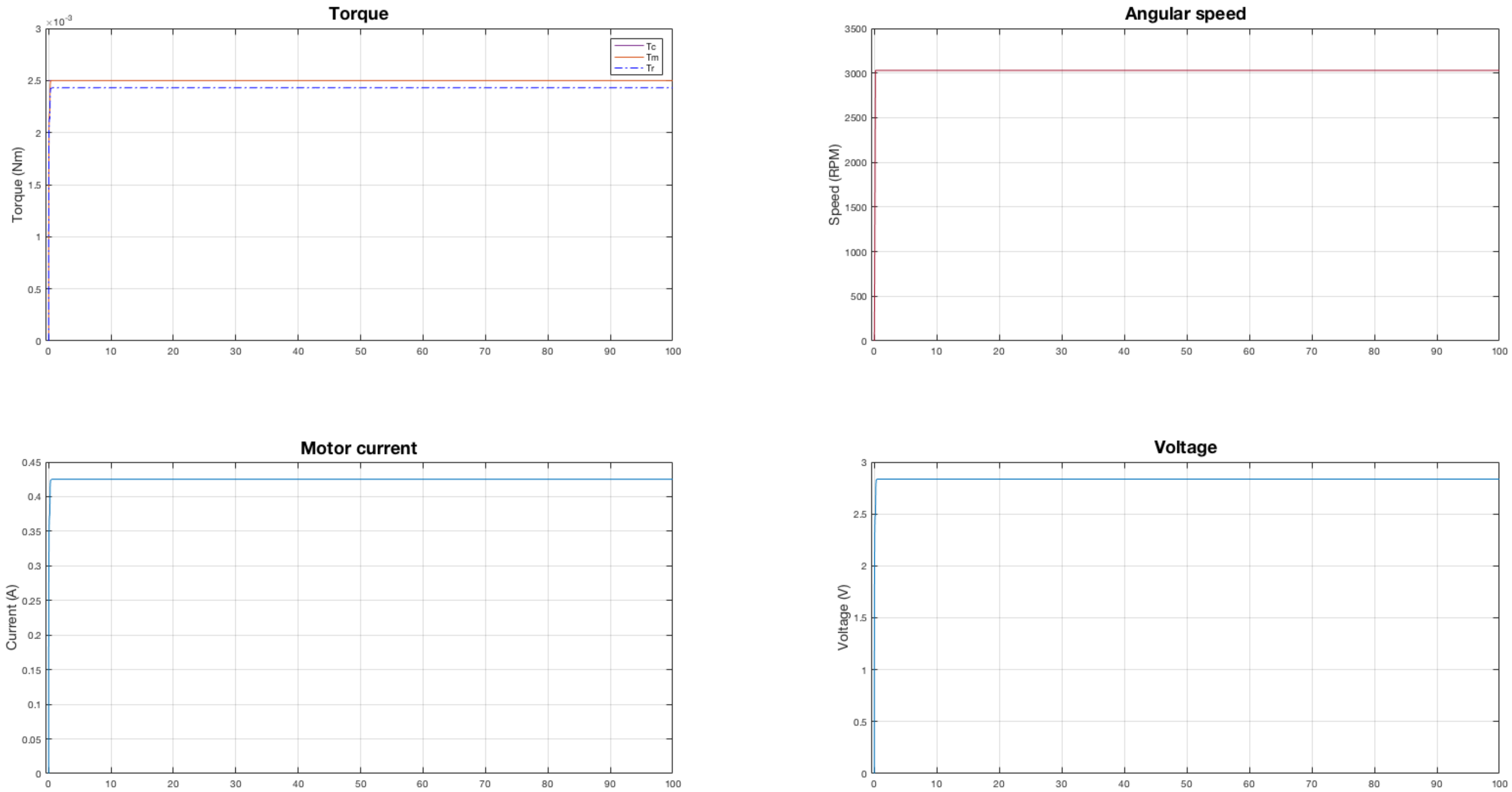

Motor current
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Current (A)
0
10
20
30
40
50
60
70
80
90
100

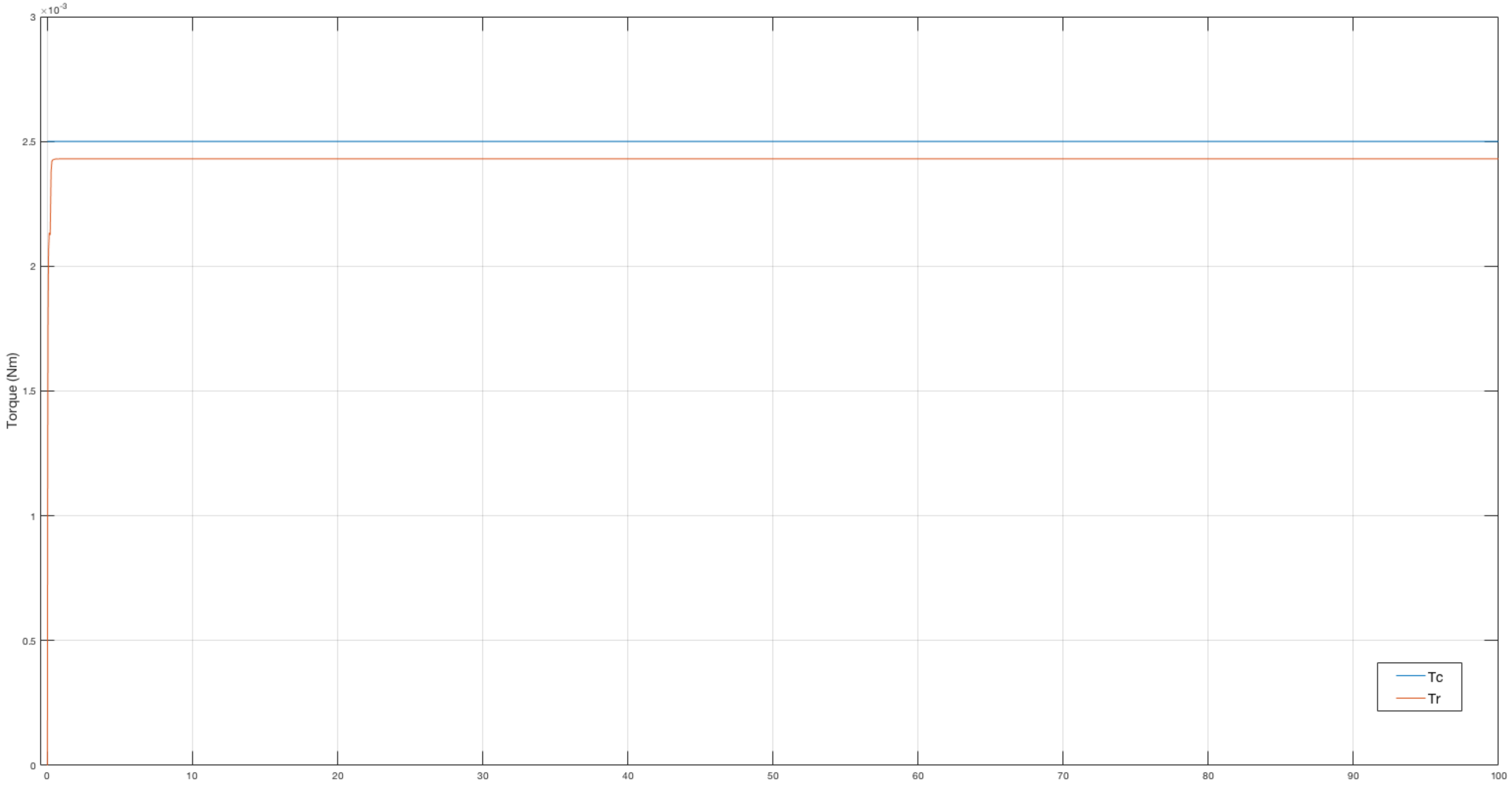

Voltage
3
2
1
0
-1
-2
-3
Voltage (V)
0
10
20
30
40
50
60
70
80
90
100


×10⁻³
3
2
1
0
-1
-2
-3
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

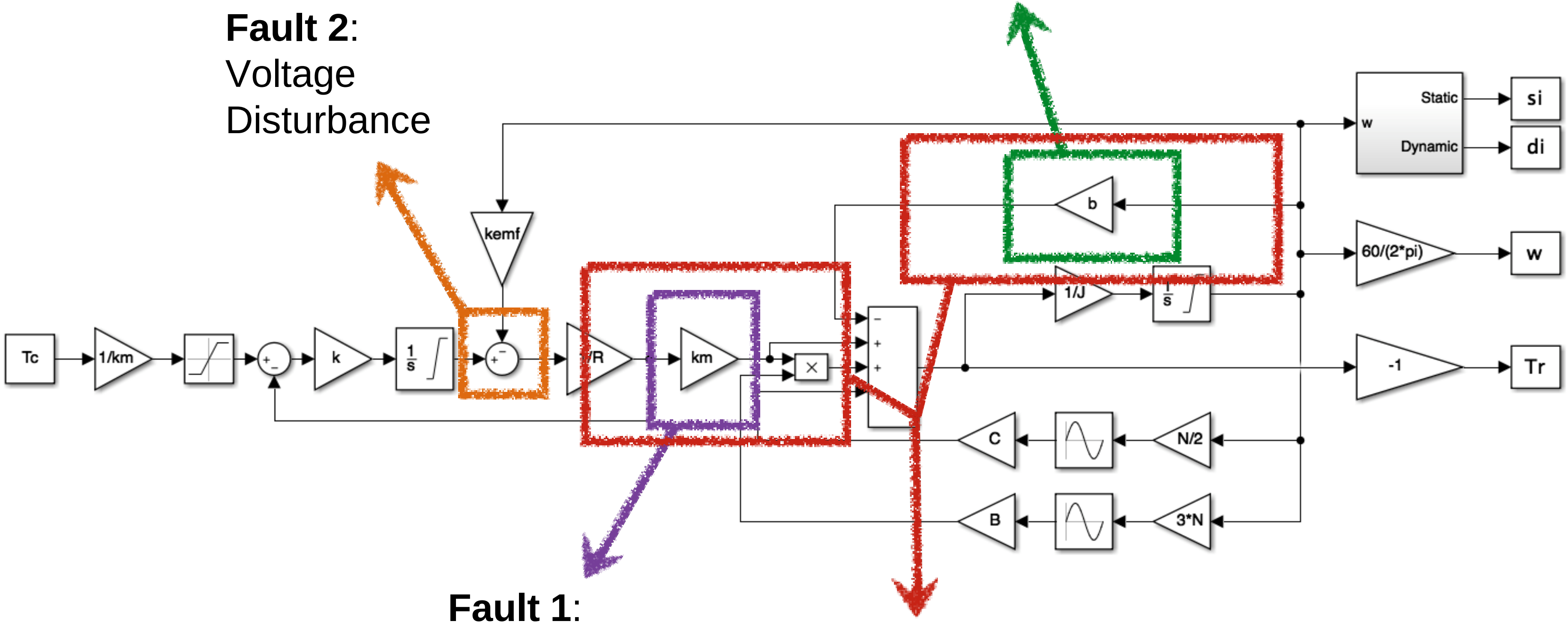

Torque
×10⁻³
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
Tc
Tm
Tr
0
10
20
30
40
50
60
70
80
90
100
Angular speed
3500
3000
2500
2000
1500
1000
500
0
Speed (RPM)
0
10
20
30
40
50
60
70
80
90
100
Motor current
0.6
0.5
0.4
0.3
0.2
0.1
0
Current (A)
0
10
20
30
40
50
60
70
80
90
100
Voltage
3.5
3
2.5
2
1.5
1
0.5
0
Voltage (V)
0
10
20
30
40
50
60
70
80
90
100


×10^-3
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr


Torque
×10^-3
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
Tc
Tm
Tr
0 10 20 30 40 50 60 70 80 90 100
Angular speed
3500
3000
2500
2000
1500
1000
500
0
Speed (RPM)
0 10 20 30 40 50 60 70 80 90 100
Motor current
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Current (A)
0 10 20 30 40 50 60 70 80 90 100
Voltage
3
2.5
2
1.5
1
0.5
0
Voltage (V)
0 10 20 30 40 50 60 70 80 90 100


×10⁻³
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

# Faulty Operation



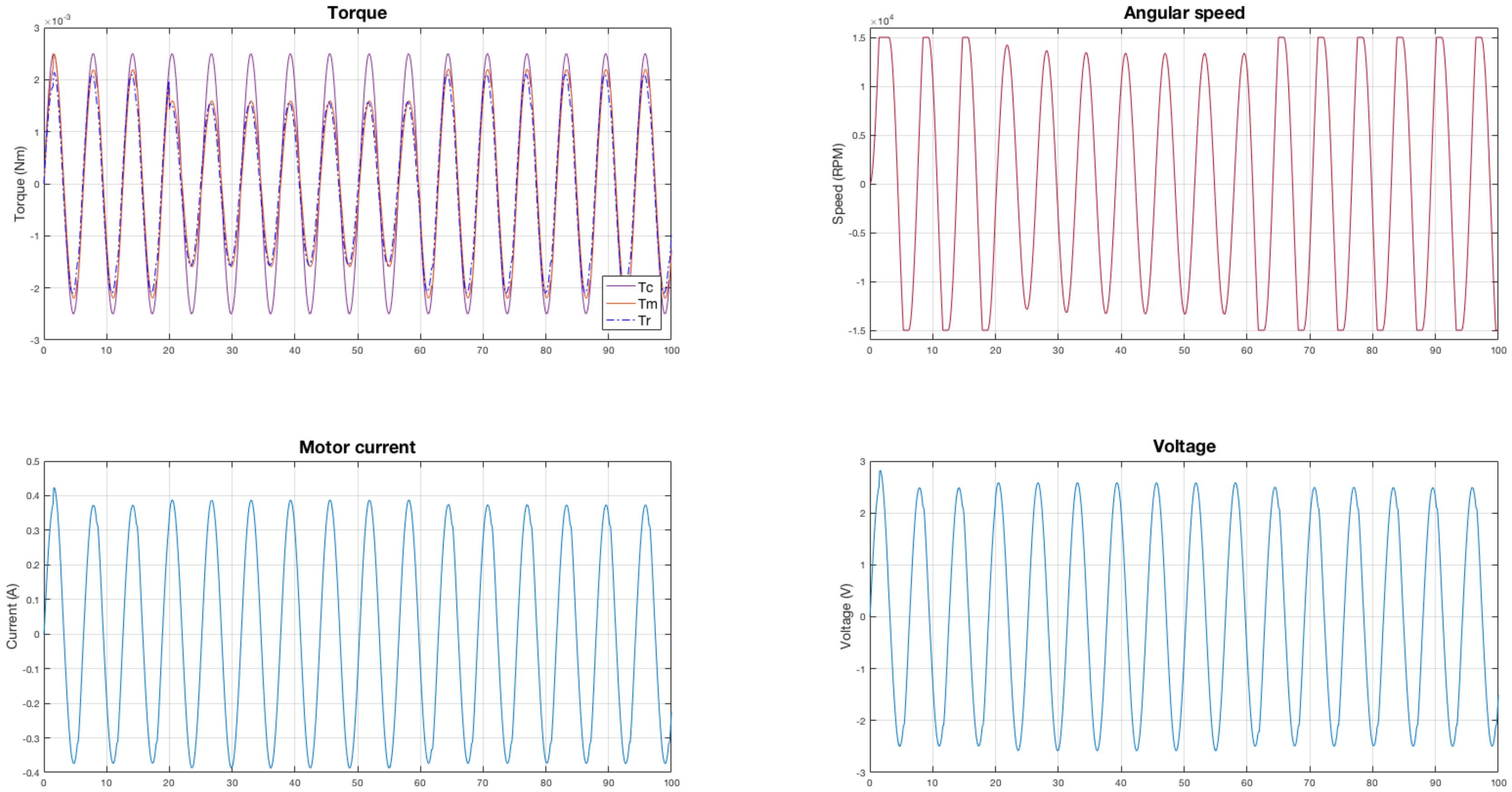
**Fault 3**:
Increase in
friction

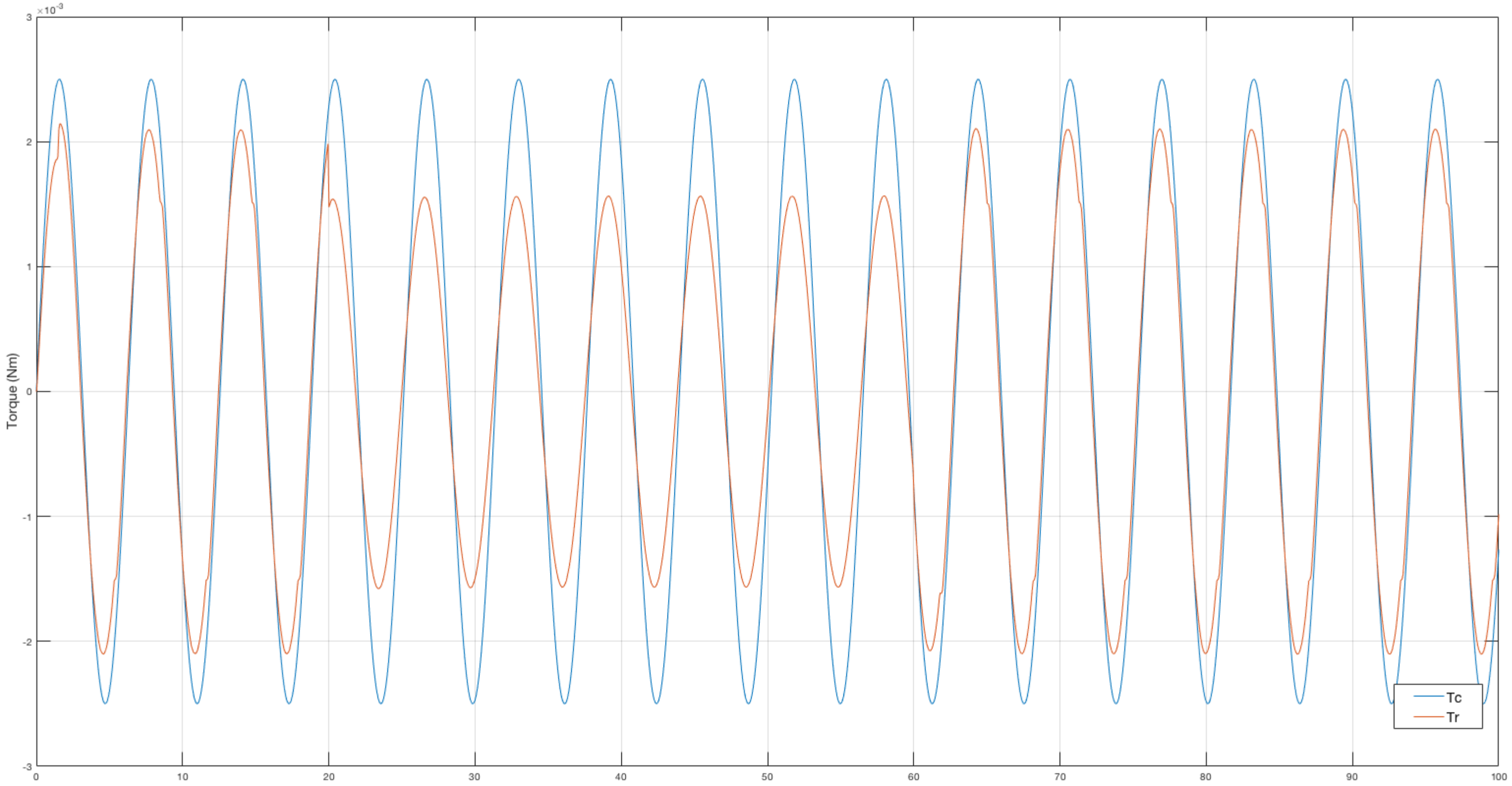
**Fault 2**:
Voltage
Disturbance

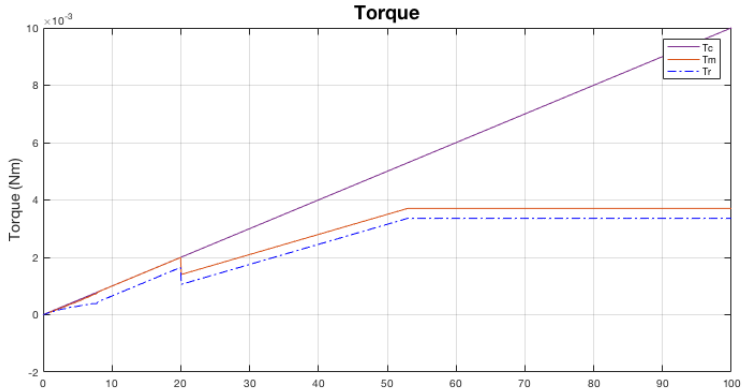
**Fault 1**:
Efficiency
loss

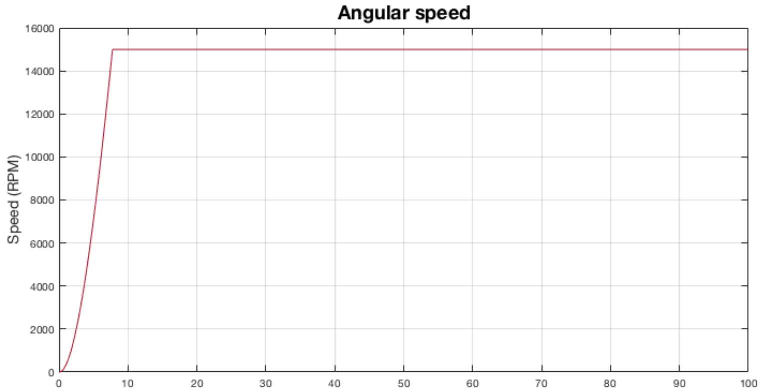
**Fault 4**:
Increase in
current with
increase in
friction

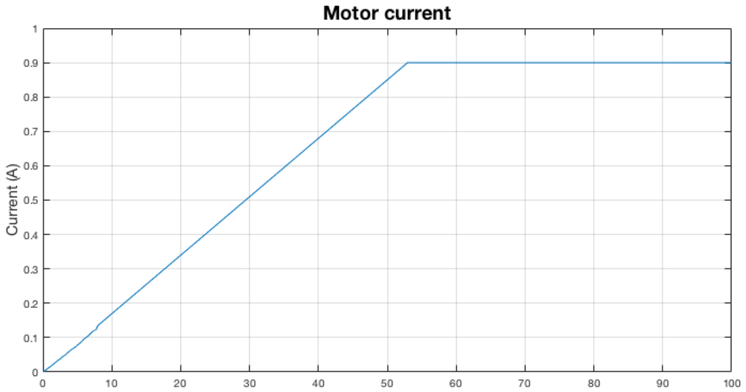
# Fault 1: $k_m^{f1}=0.7k_m^n$

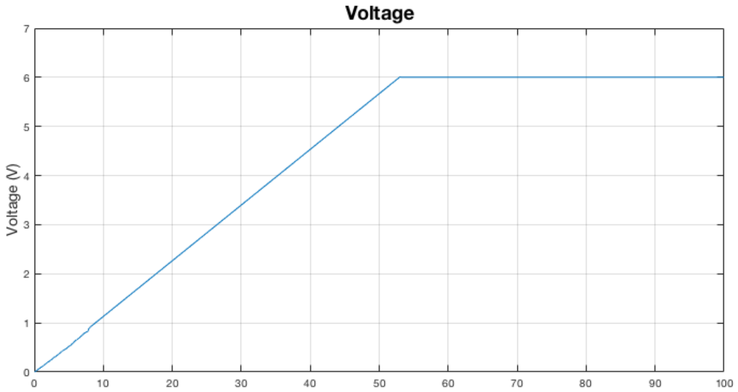


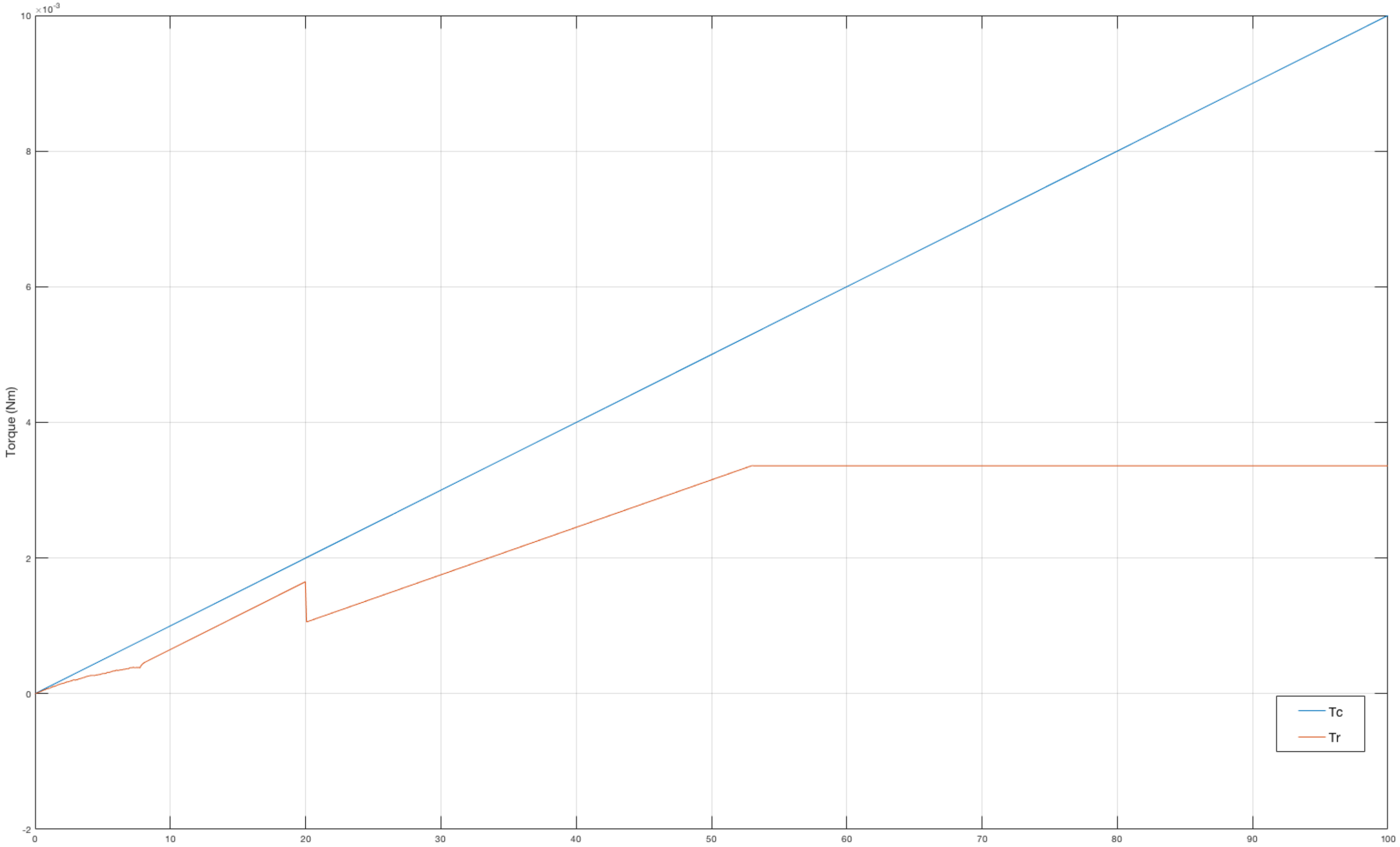

×10⁻³
3
2
1
0
-1
-2
-3
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

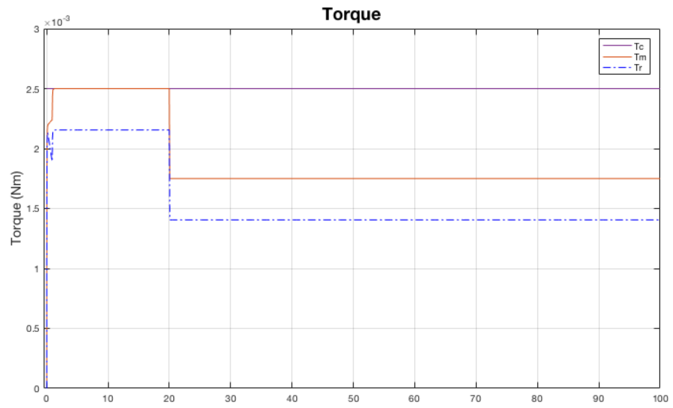

Torque

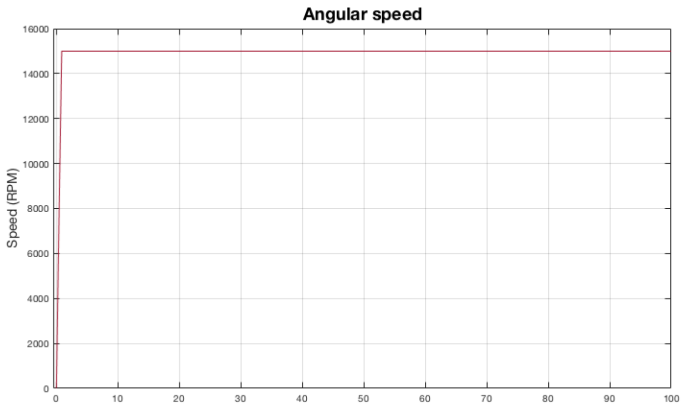

Angular speed

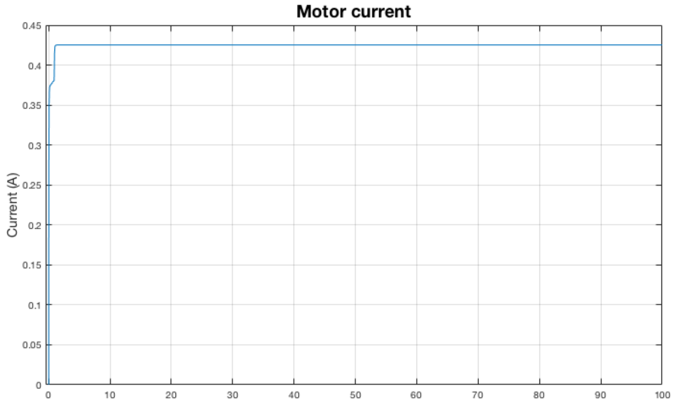

Motor current

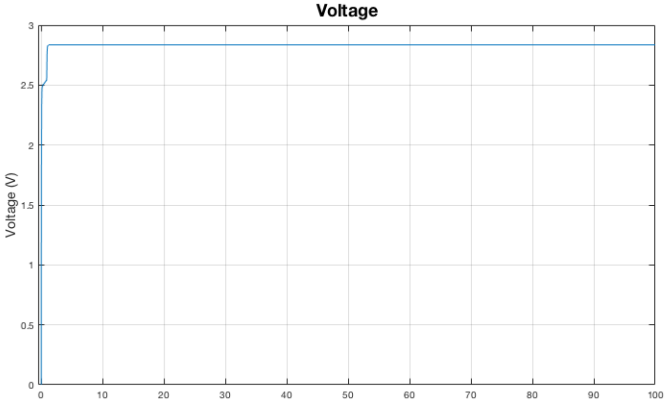

Voltage

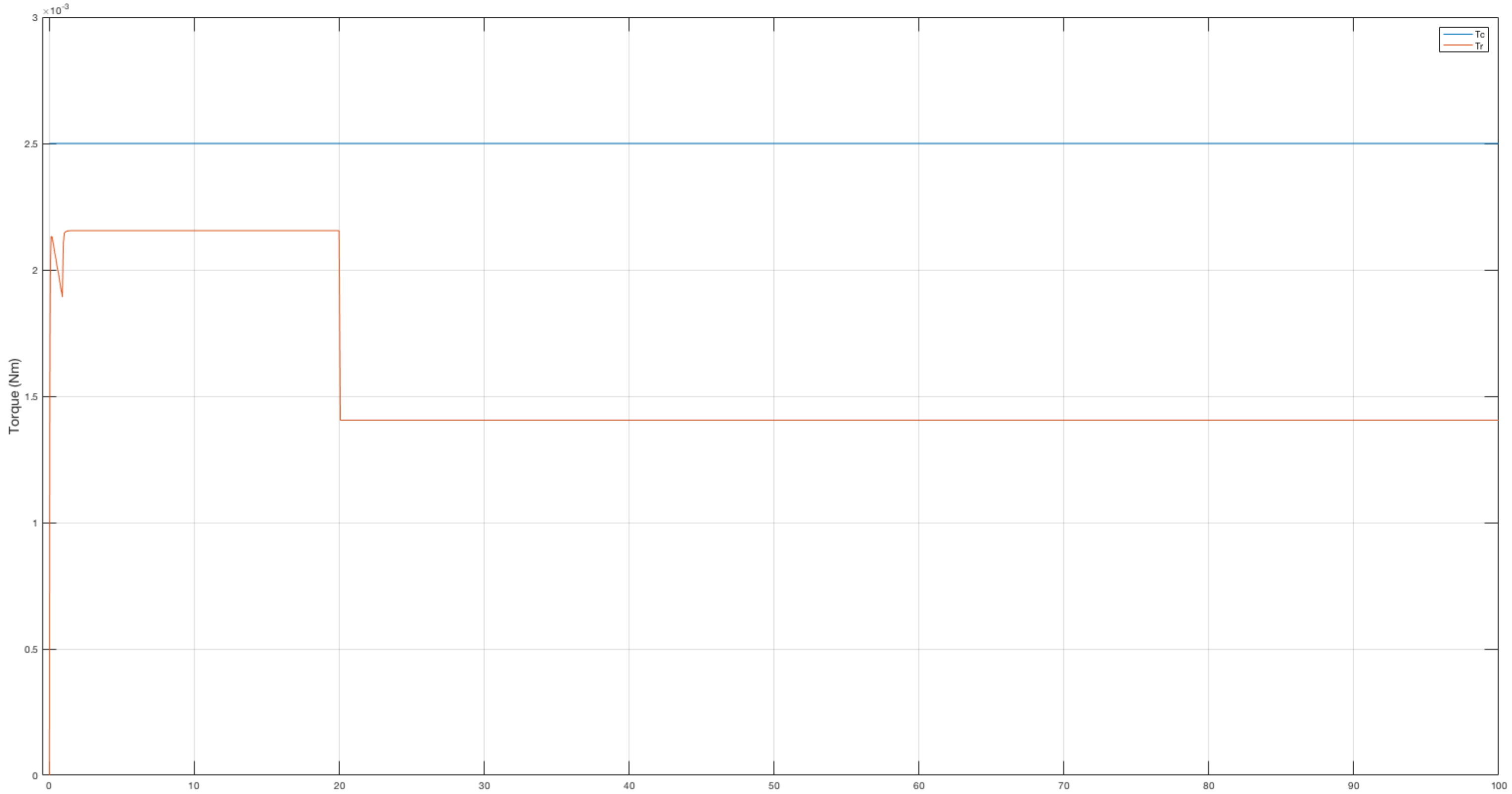
×10⁻³
Torque (Nm)
10
8
6
4
2
0
-2
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr


Torque

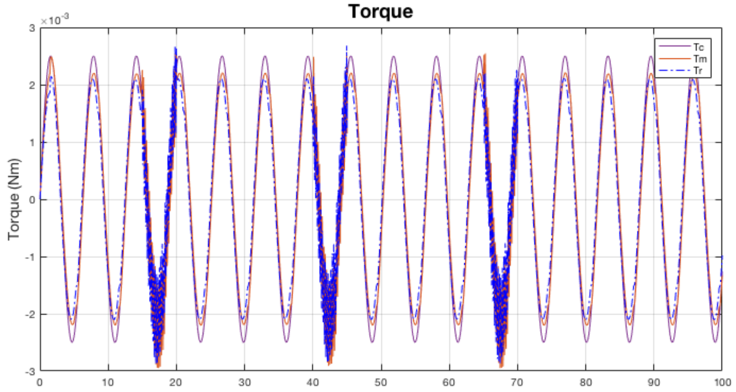

Angular speed

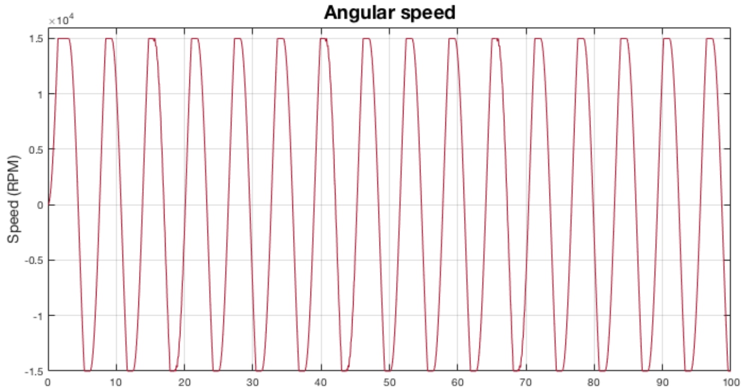

Motor current

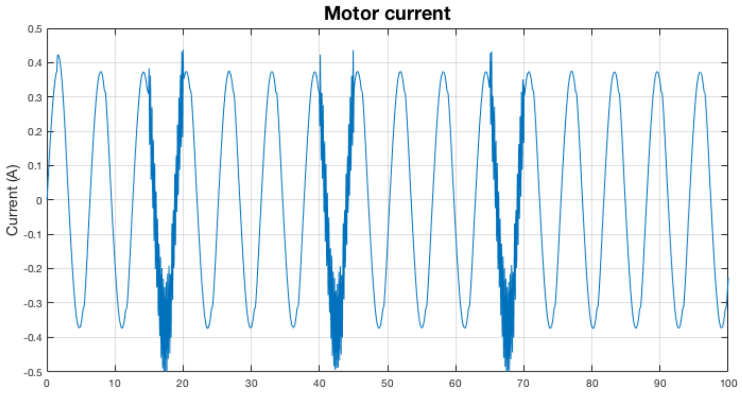

Voltage

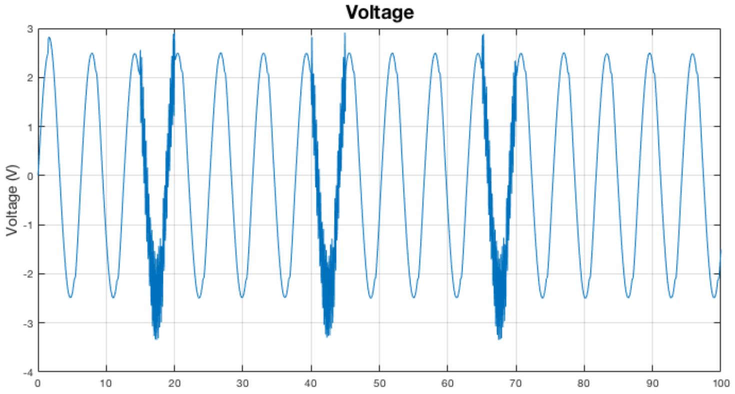

×10⁻³
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

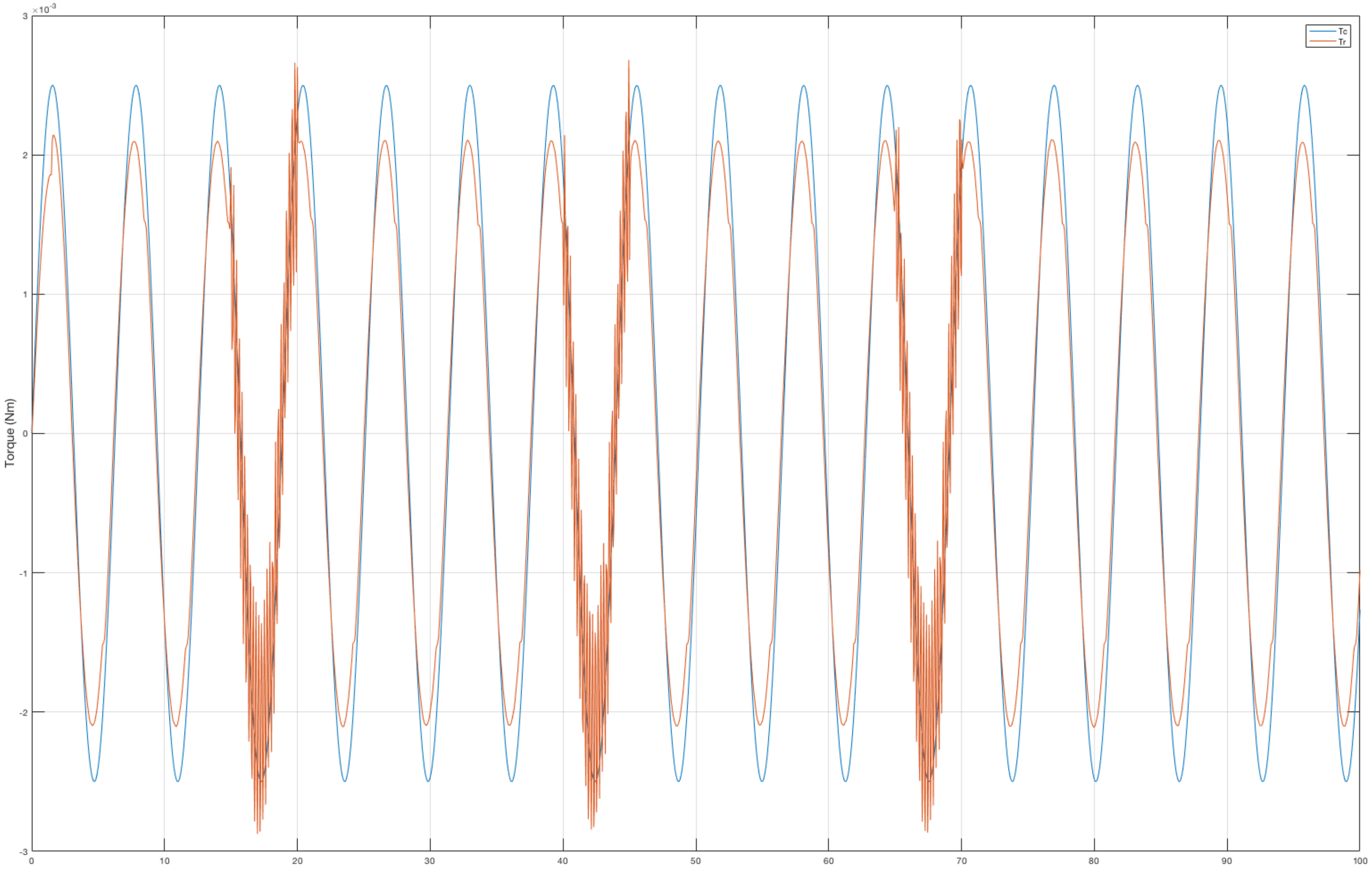
# =1.5*sin(30*t)

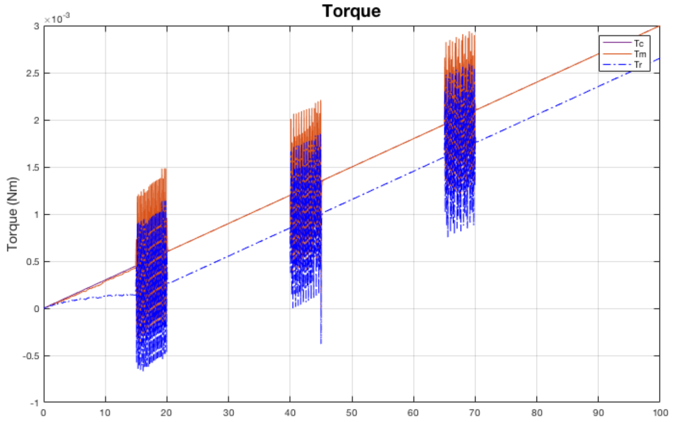

Torque
×10⁻³
Torque (Nm)
Tc
Tm
Tr
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
70
80
90
100

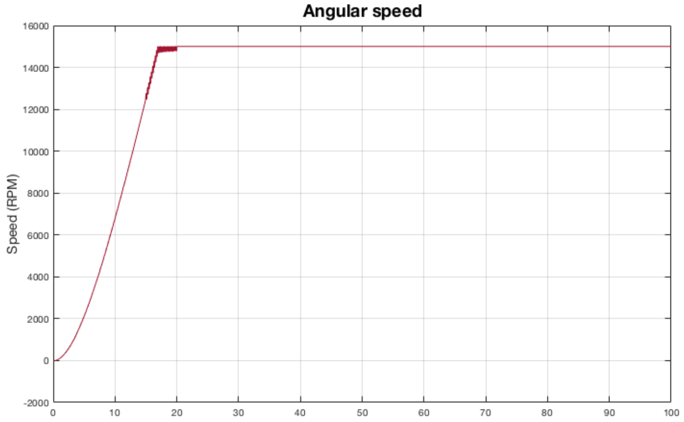

Angular speed
×10⁴
Speed (RPM)
1.5
1
0.5
0
-0.5
-1
-1.5
0
10
20
30
40
50
60
70
80
90
100

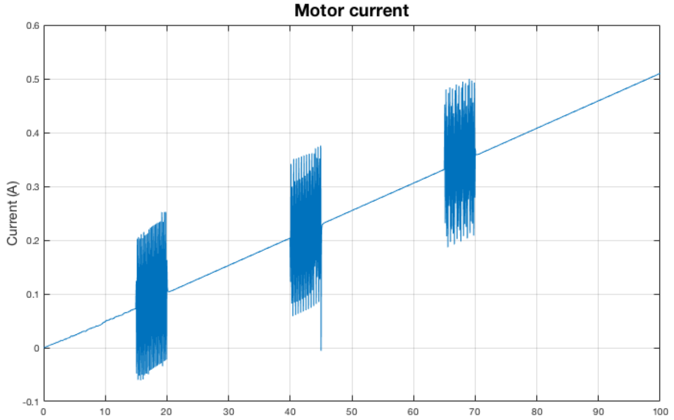

Motor current
Current (A)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
10
20
30
40
50
60
70
80
90
100

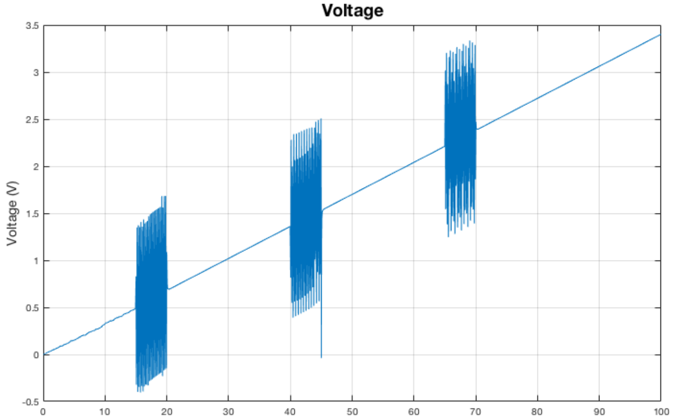

Voltage
Voltage (V)
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
50
60
70
80
90
100

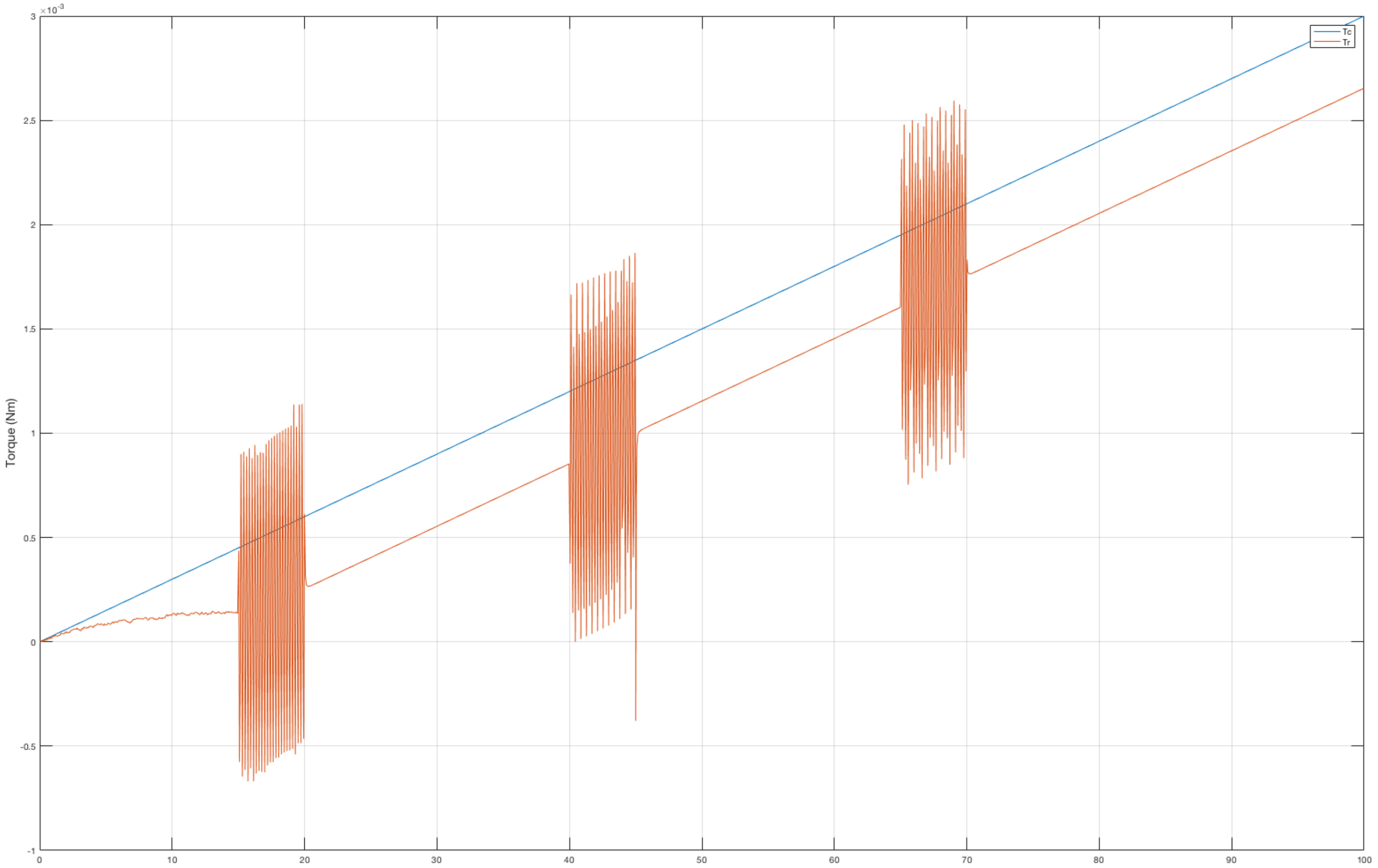

×10⁻³
3
2
1
0
-1
-2
-3
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

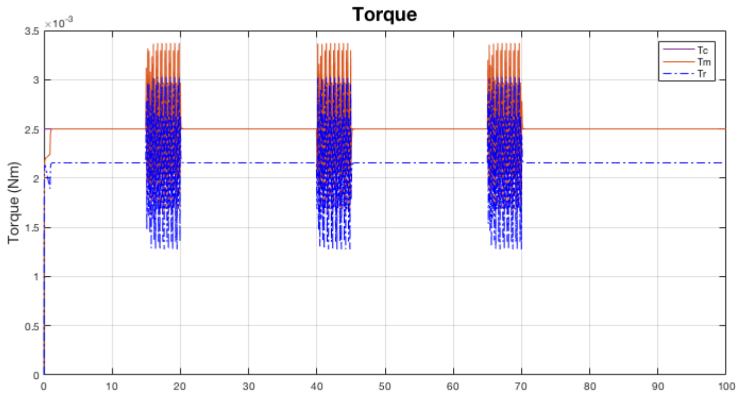

Torque
×10⁻³
Torque (Nm)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
10
20
30
40
50
60
70
80
90
100
Tc
Tm
Tr

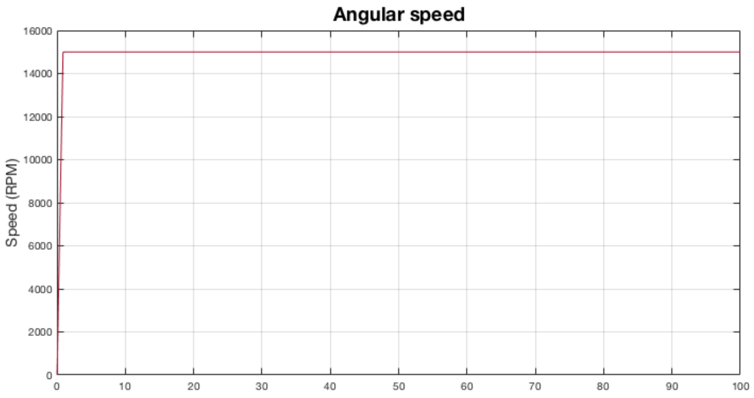

Angular speed
Speed (RPM)
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
0
10
20
30
40
50
60
70
80
90
100

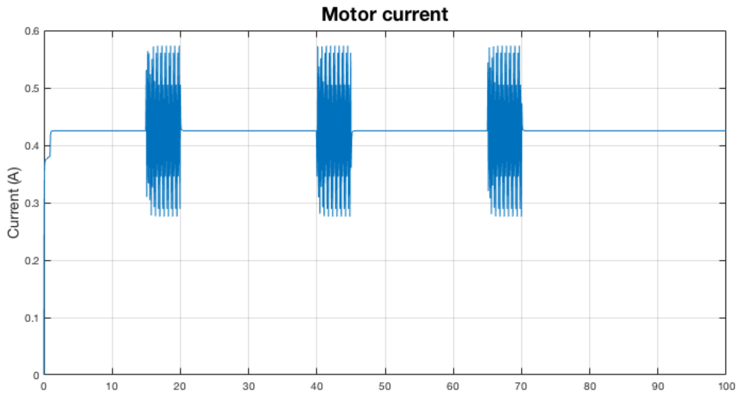

Motor current
Current (A)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
10
20
30
40
50
60
70
80
90
100

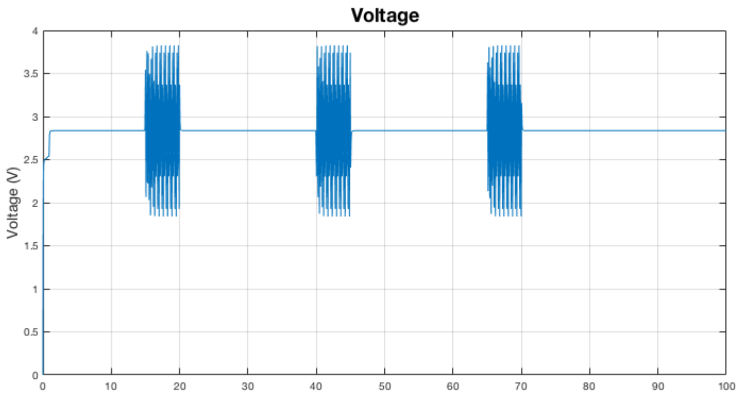

Voltage
Voltage (V)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
10
20
30
40
50
60
70
80
90
100

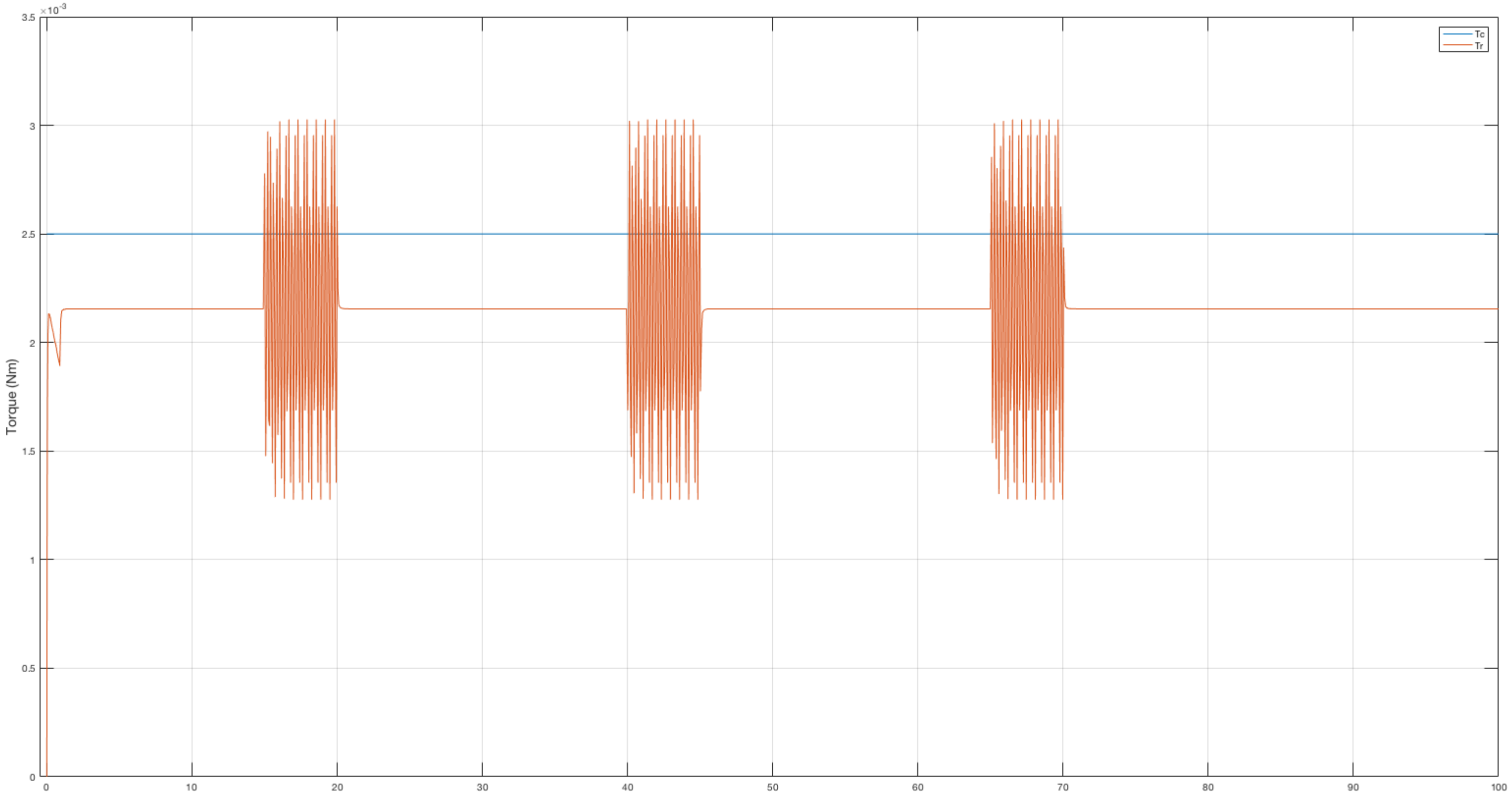

×10⁻³
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr


Torque


Angular speed

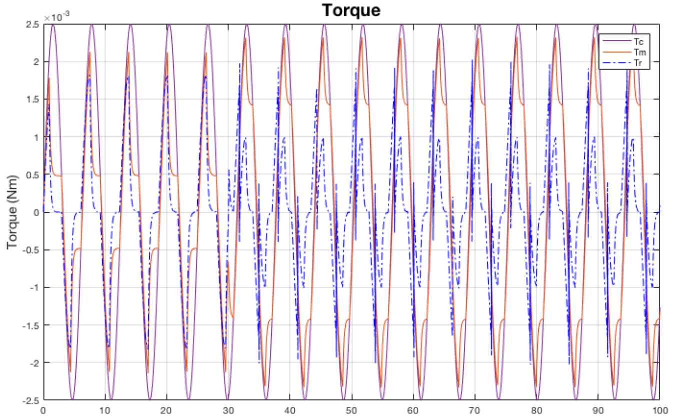

Motor current

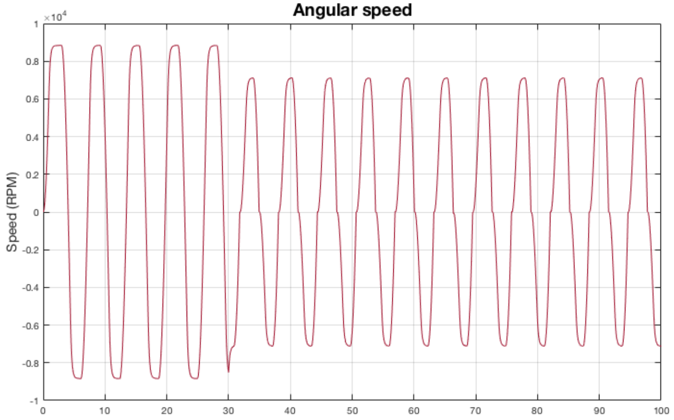

Voltage

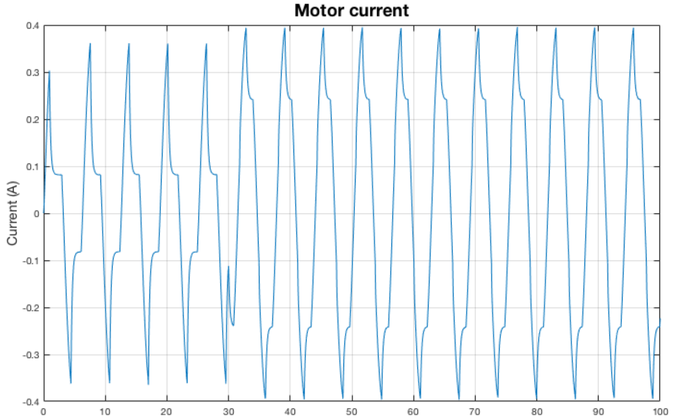


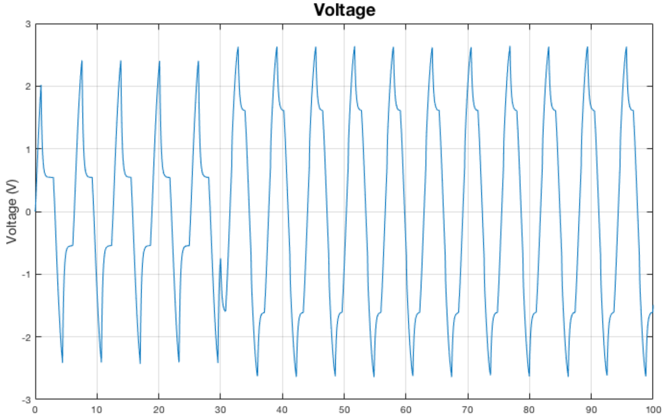
×10⁻³
3.5
3
2.5
2
1.5
1
0.5
0
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

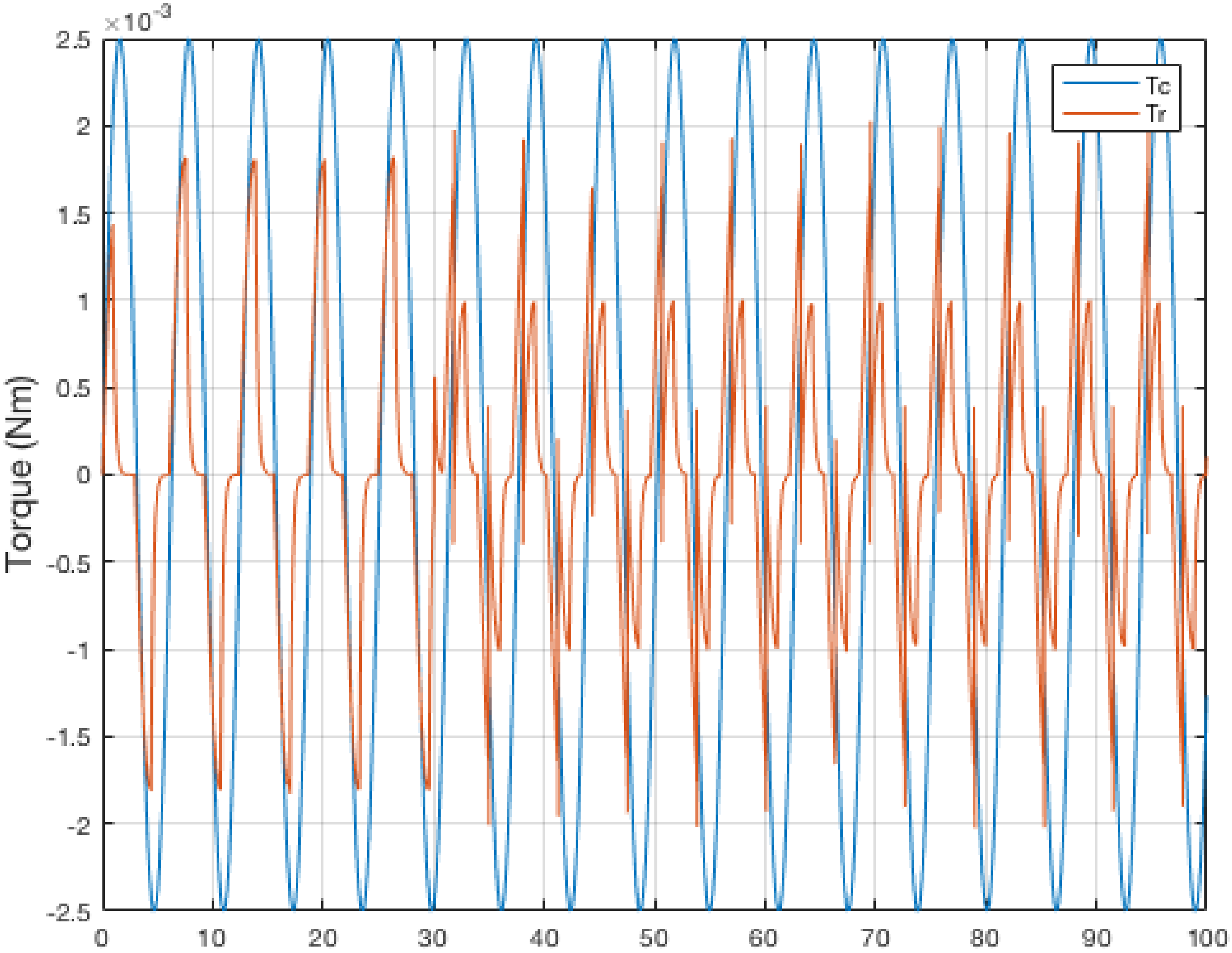
# Increase

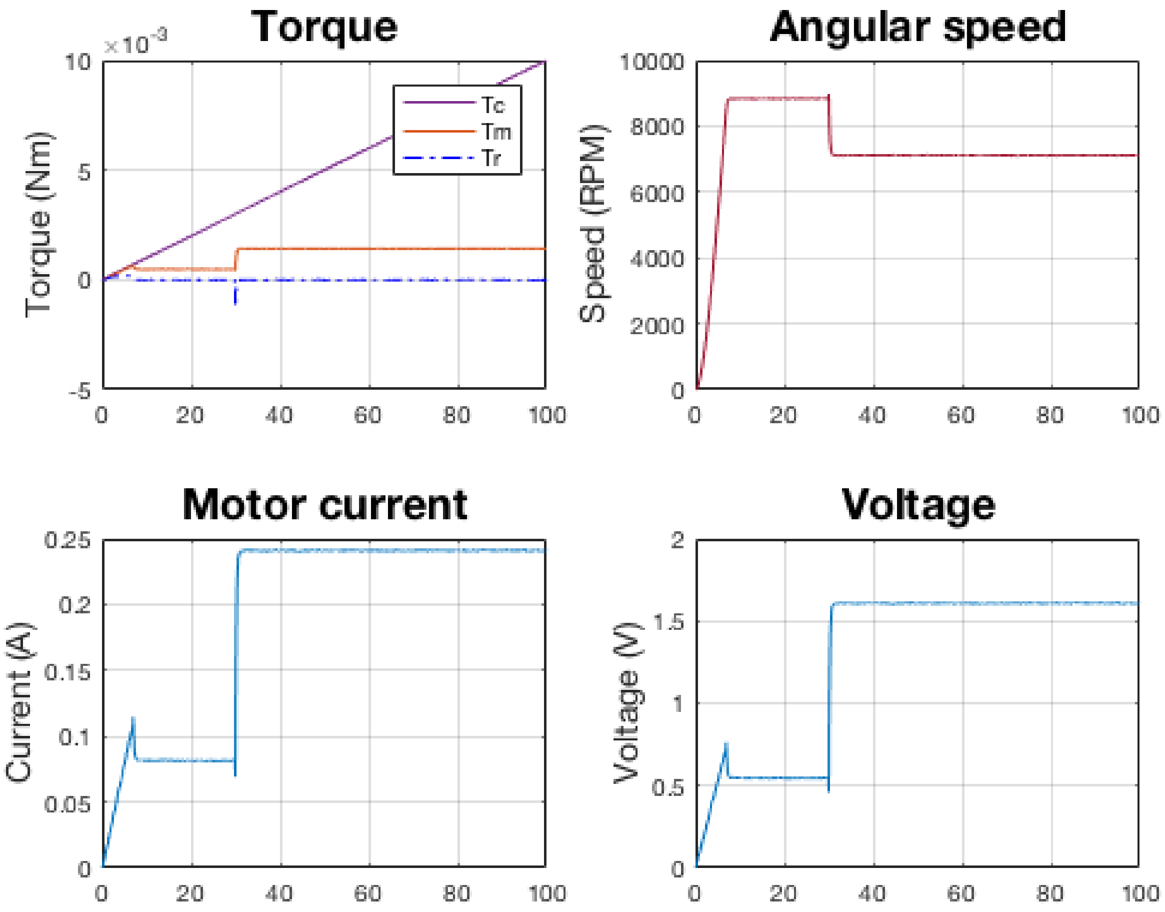

Torque
×10^-3
Torque (Nm)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
60
70
80
90
100
Tc
Tm
Tr

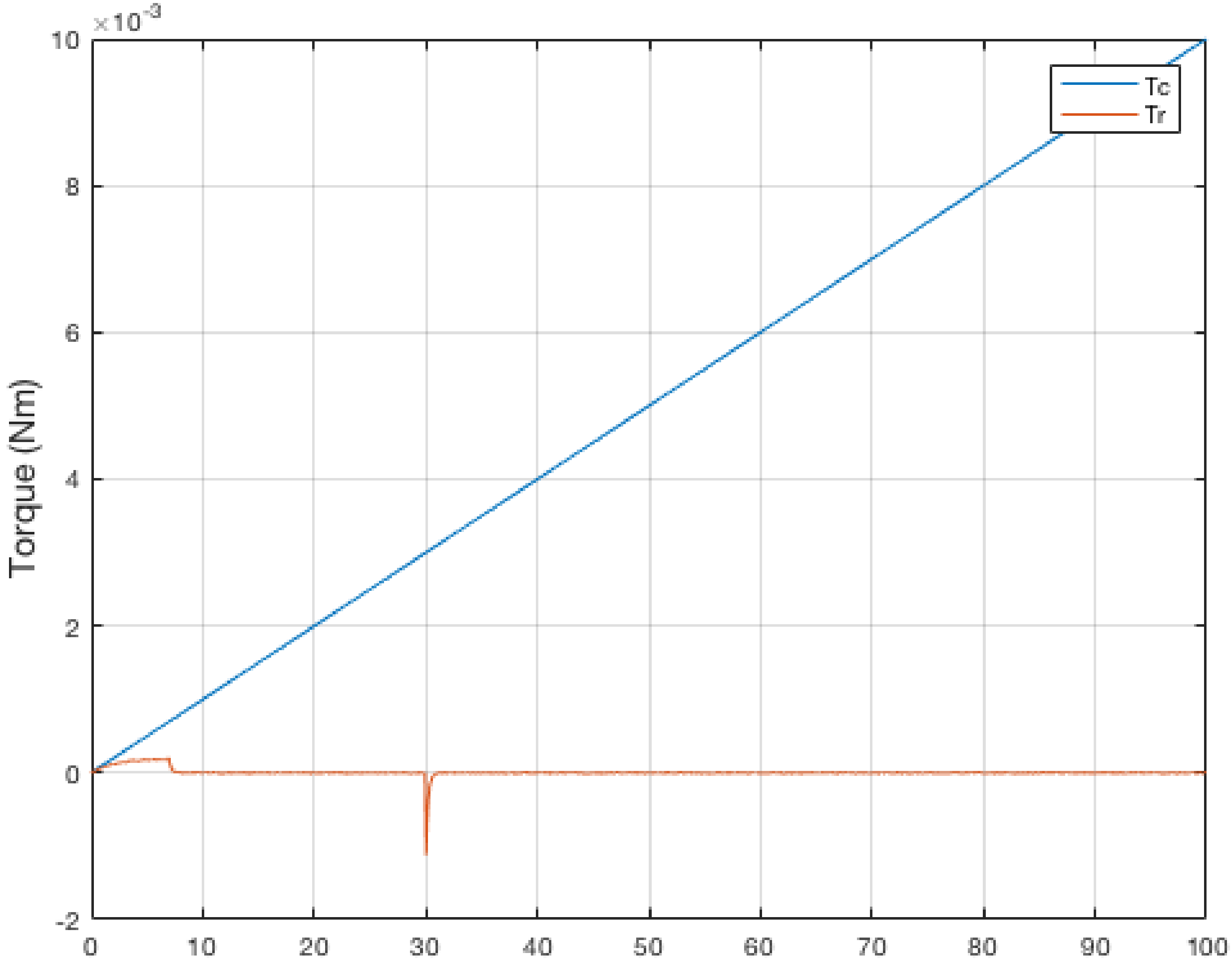

Angular speed
×10^4
Speed (RPM)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
10
20
30
40
50
60
70
80
90
100

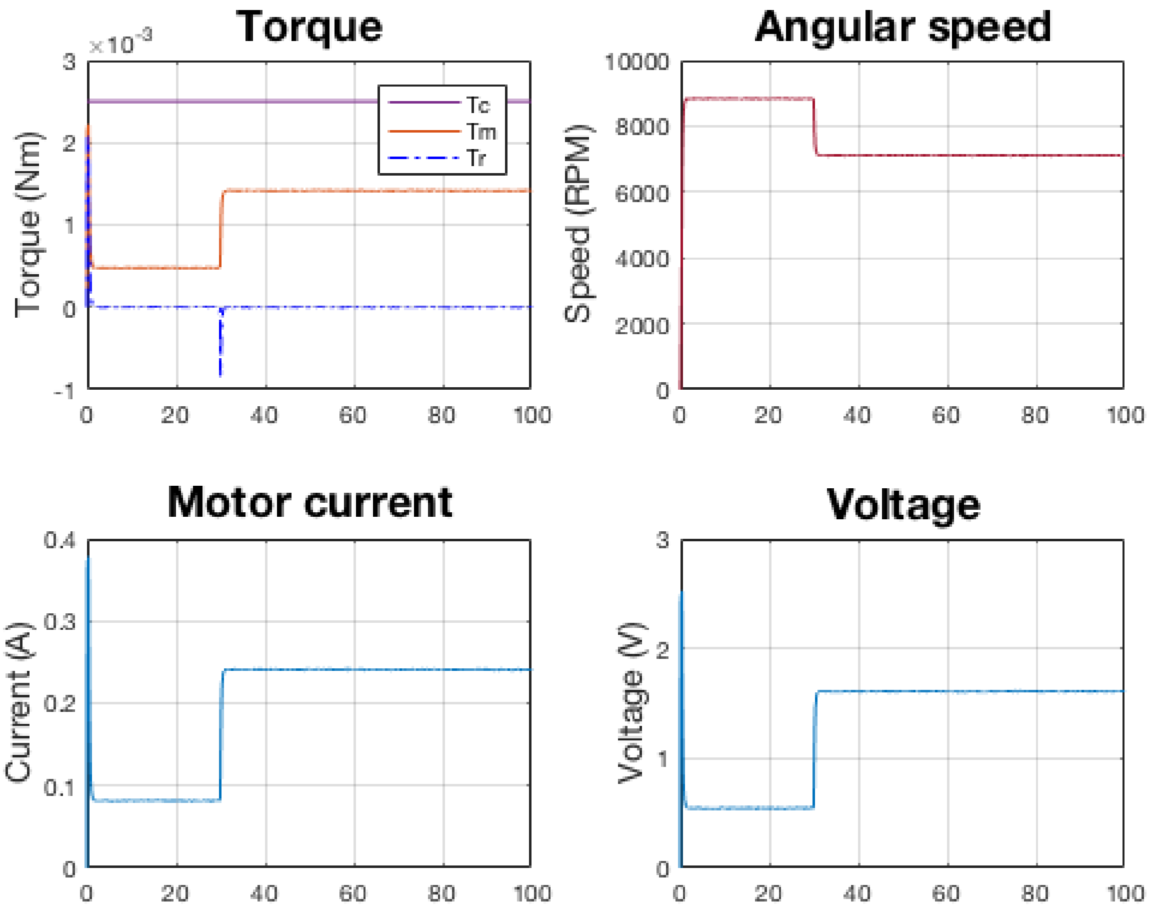

Motor current
Current (A)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
10
20
30
40
50
60
70
80
90
100

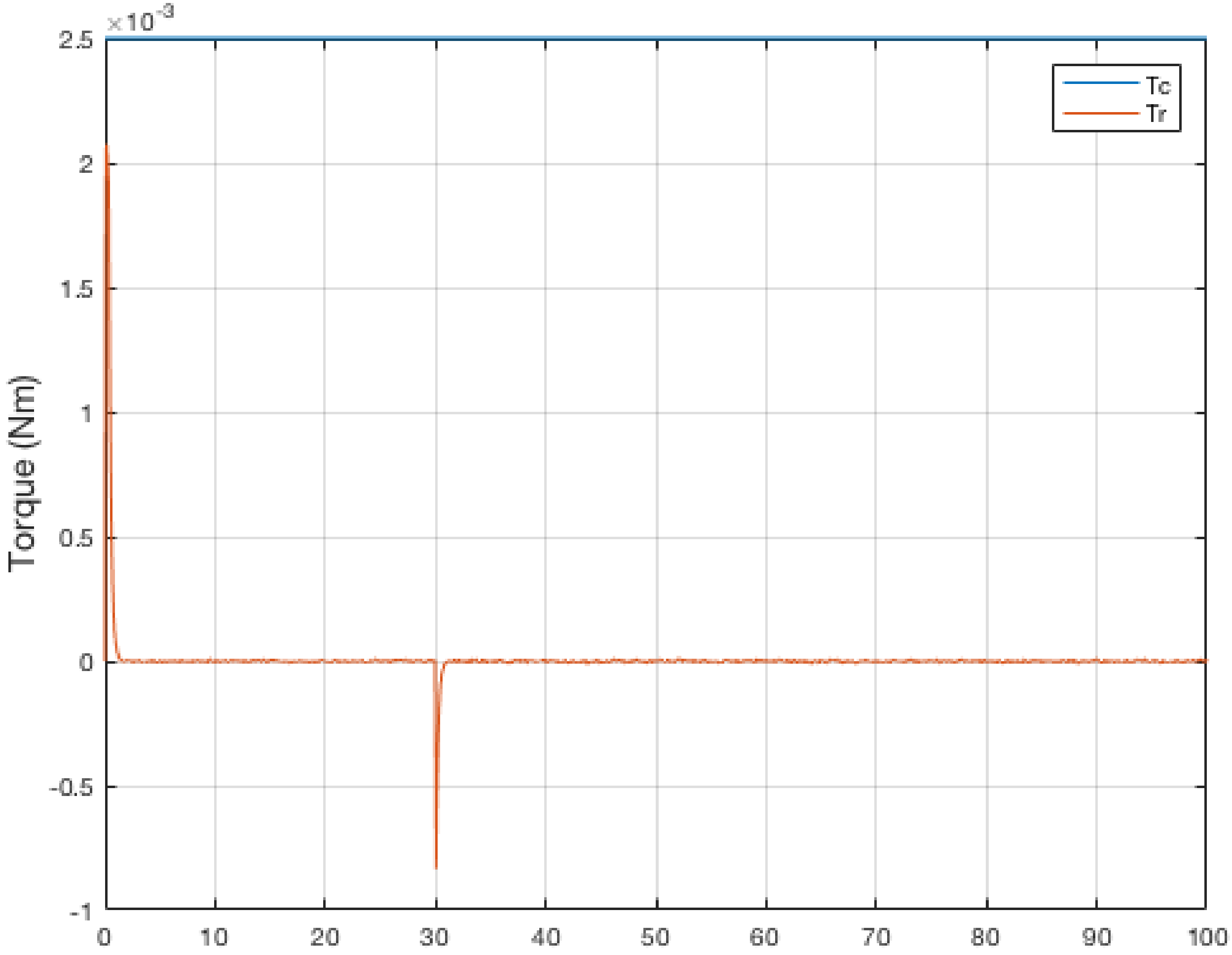

Voltage
Voltage (V)
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
70
80
90
100


×10^-3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

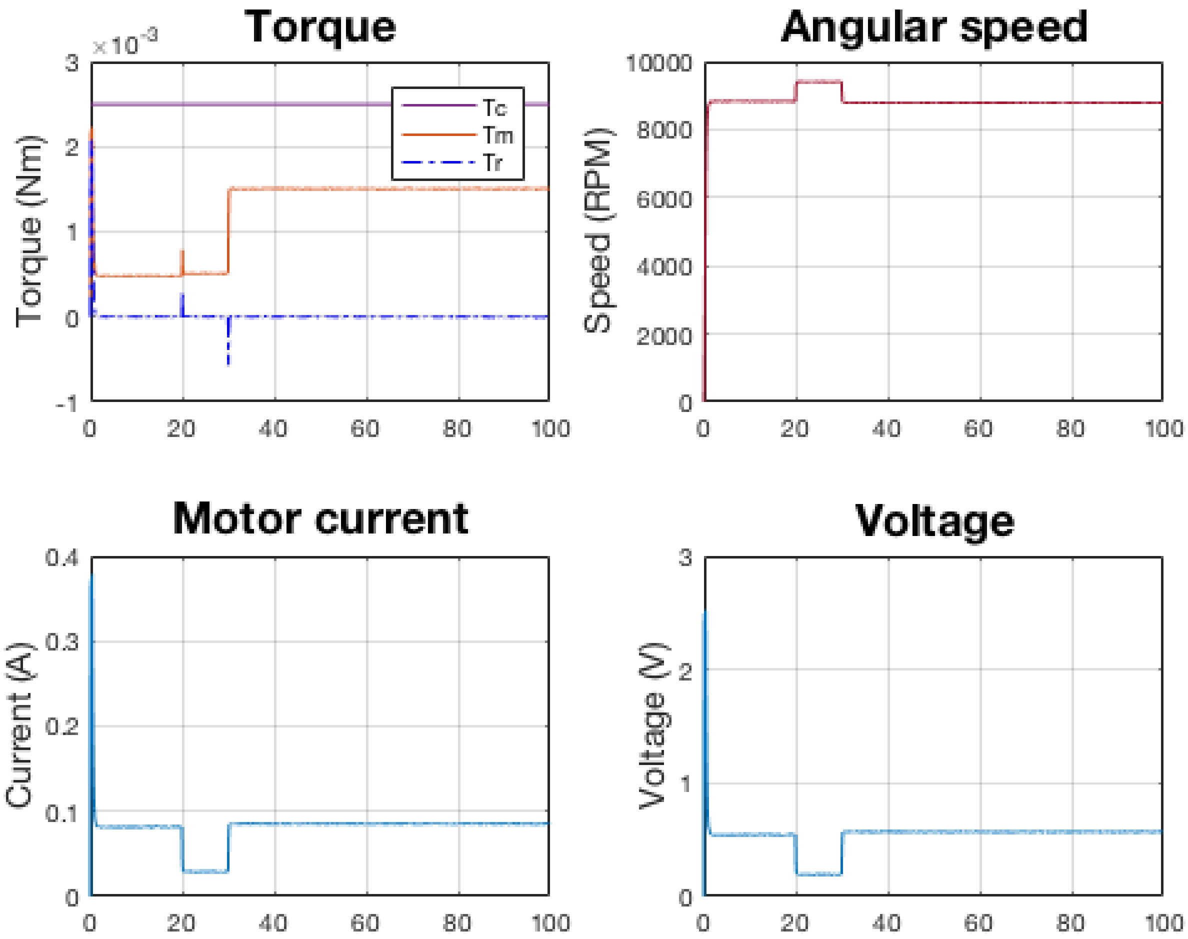
Torque
×10⁻³
10
5
0
-5
Torque (Nm)
Tc
Tm
Tr
0
20
40
60
80
100
Angular speed
10000
8000
6000
4000
2000
0
Speed (RPM)
0
20
40
60
80
100
Motor current
0.25
0.2
0.15
0.1
0.05
0
Current (A)
0
20
40
60
80
100
Voltage
2
1.5
1
0.5
0
Voltage (V)
0
20
40
60
80
100

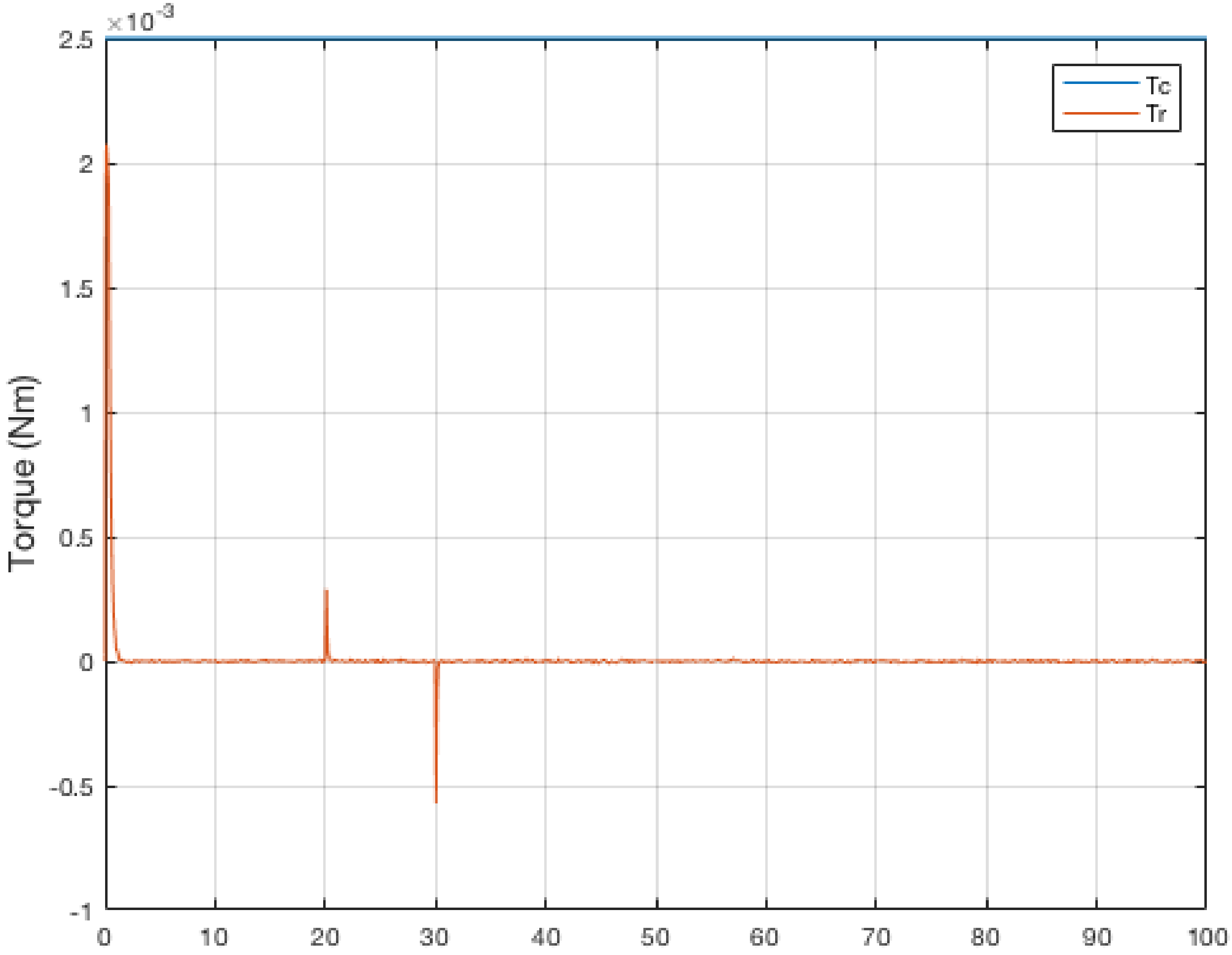

×10^-3
10
8
6
4
2
0
-2
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

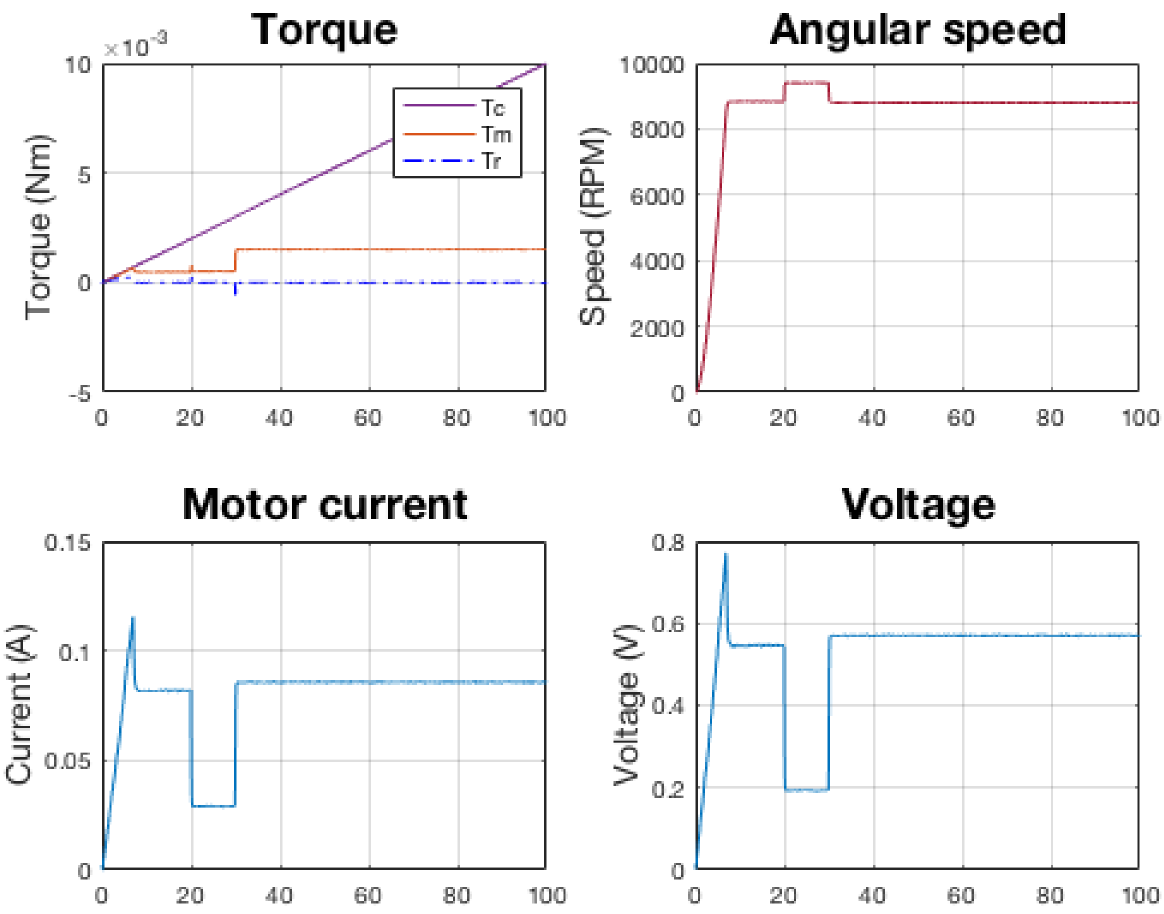

Torque
×10^-3
3
2
1
0
-1
Torque (Nm)
Tc
Tm
Tr
0
20
40
60
80
100
Angular speed
10000
8000
6000
4000
2000
0
Speed (RPM)
0
20
40
60
80
100
Motor current
0.4
0.3
0.2
0.1
0
Current (A)
0
20
40
60
80
100
Voltage
3
2
1
0
Voltage (V)
0
20
40
60
80
100

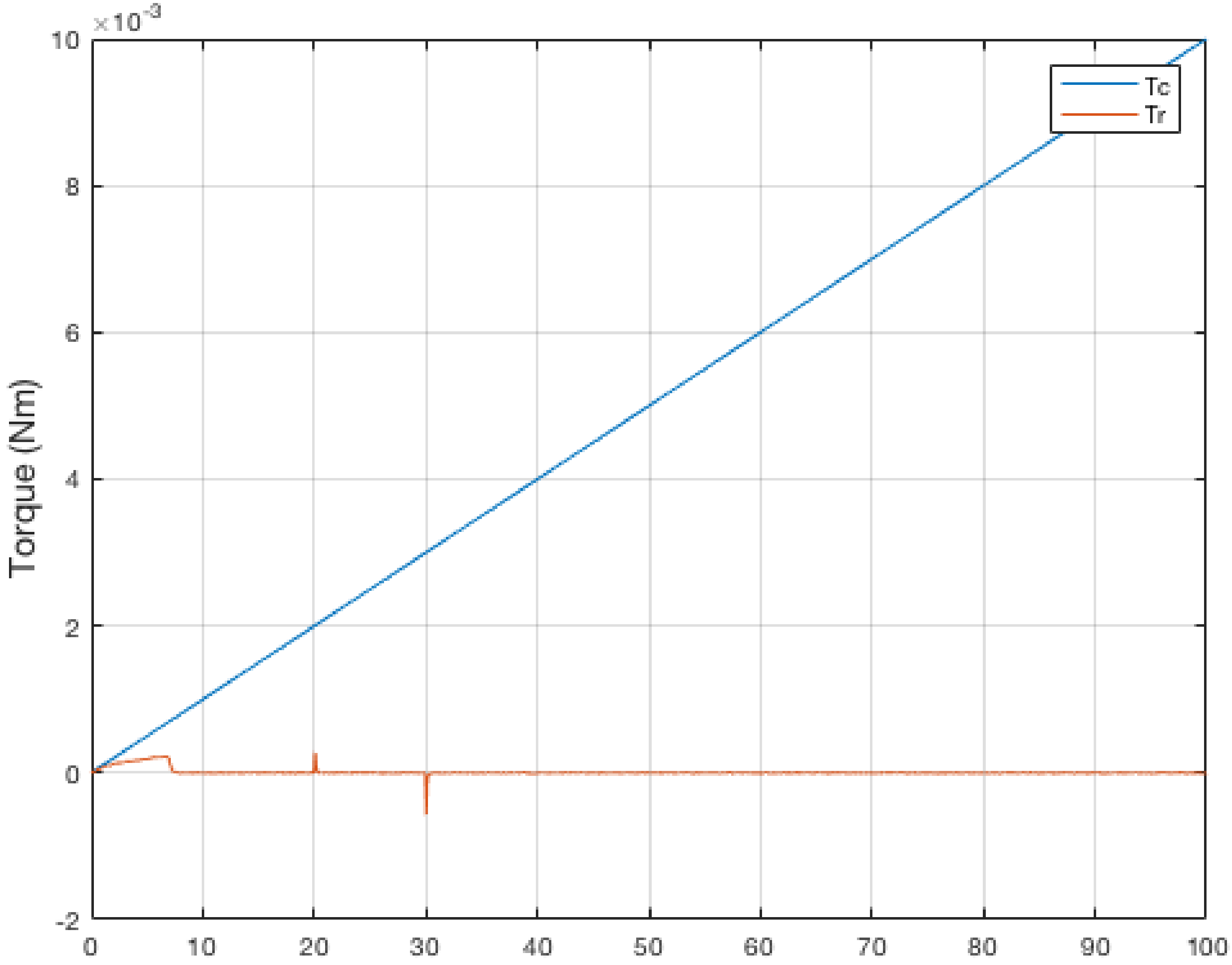

×10^-3
2.5
2
1.5
1
0.5
0
-0.5
-1
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

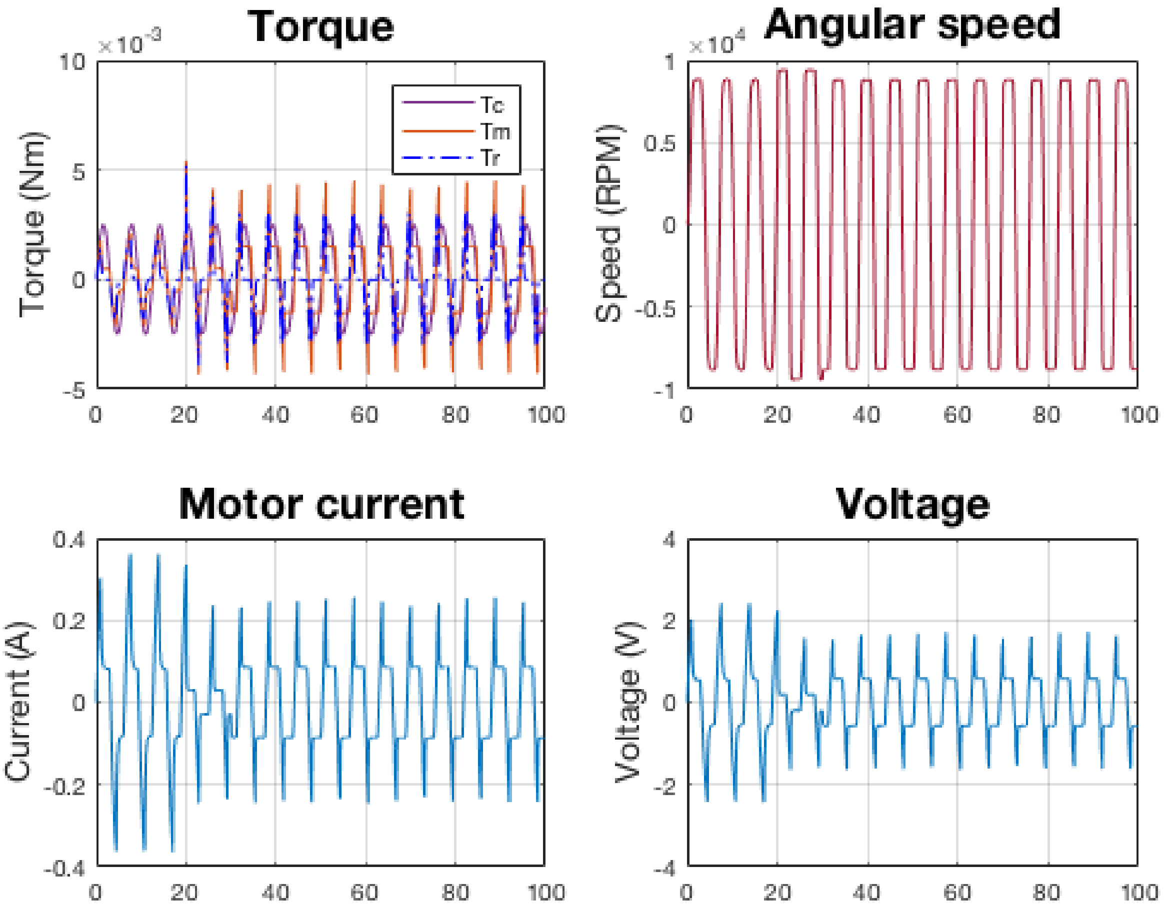
# Fault 4: $k_m^{f4}=0.7k_m^n$




×10^-3
2.5
2
1.5
1
0.5
0
-0.5
-1
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr


Torque
×10⁻³
10
5
0
-5
Torque (Nm)
Tc
Tm
Tr
0
20
40
60
80
100
Angular speed
10000
8000
6000
4000
2000
0
Speed (RPM)
0
20
40
60
80
100
Motor current
0.15
0.1
0.05
0
Current (A)
0
20
40
60
80
100
Voltage
0.8
0.6
0.4
0.2
0
Voltage (V)
0
20
40
60
80
100


×10^-3
10
8
6
4
2
0
-2
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

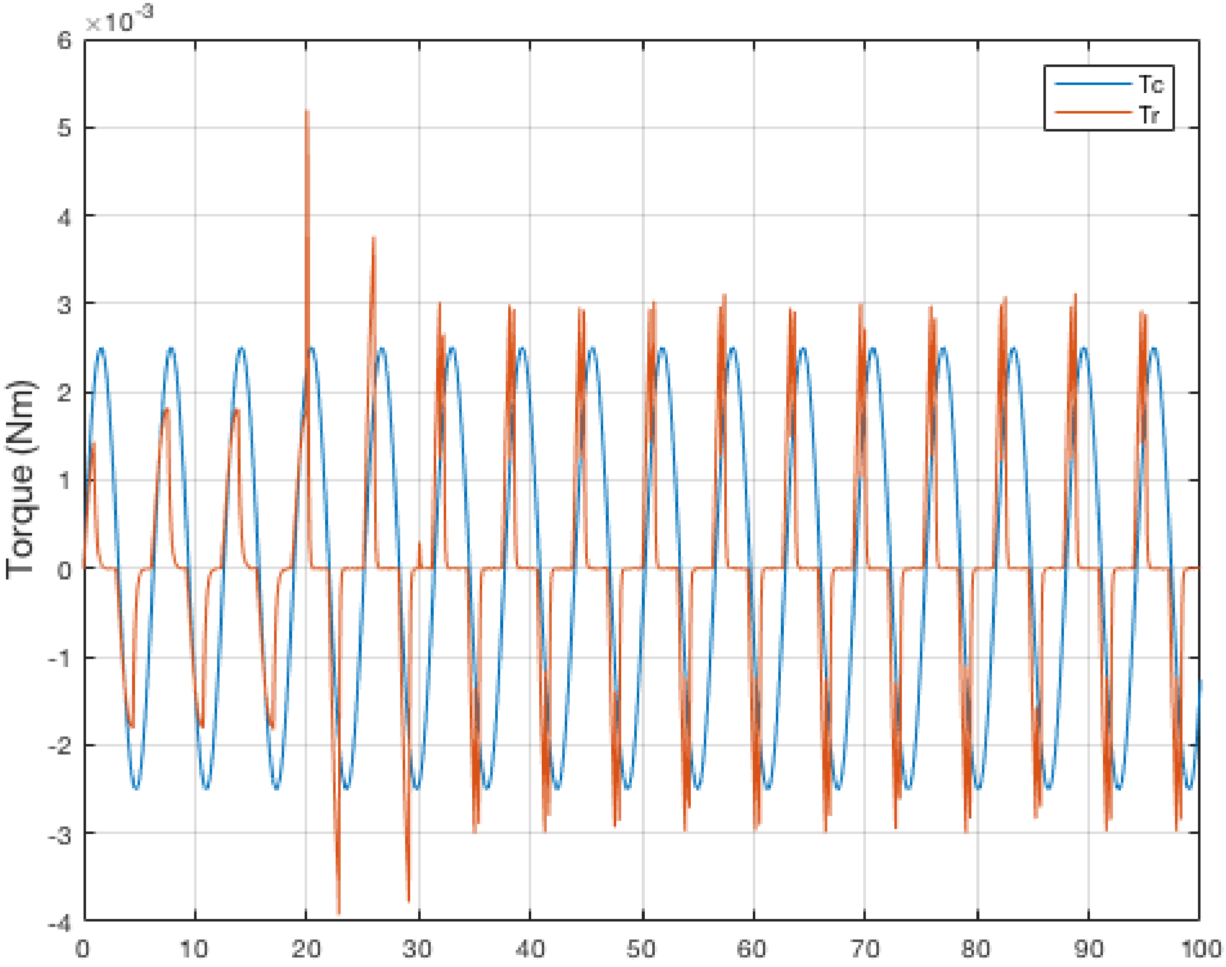


Torque

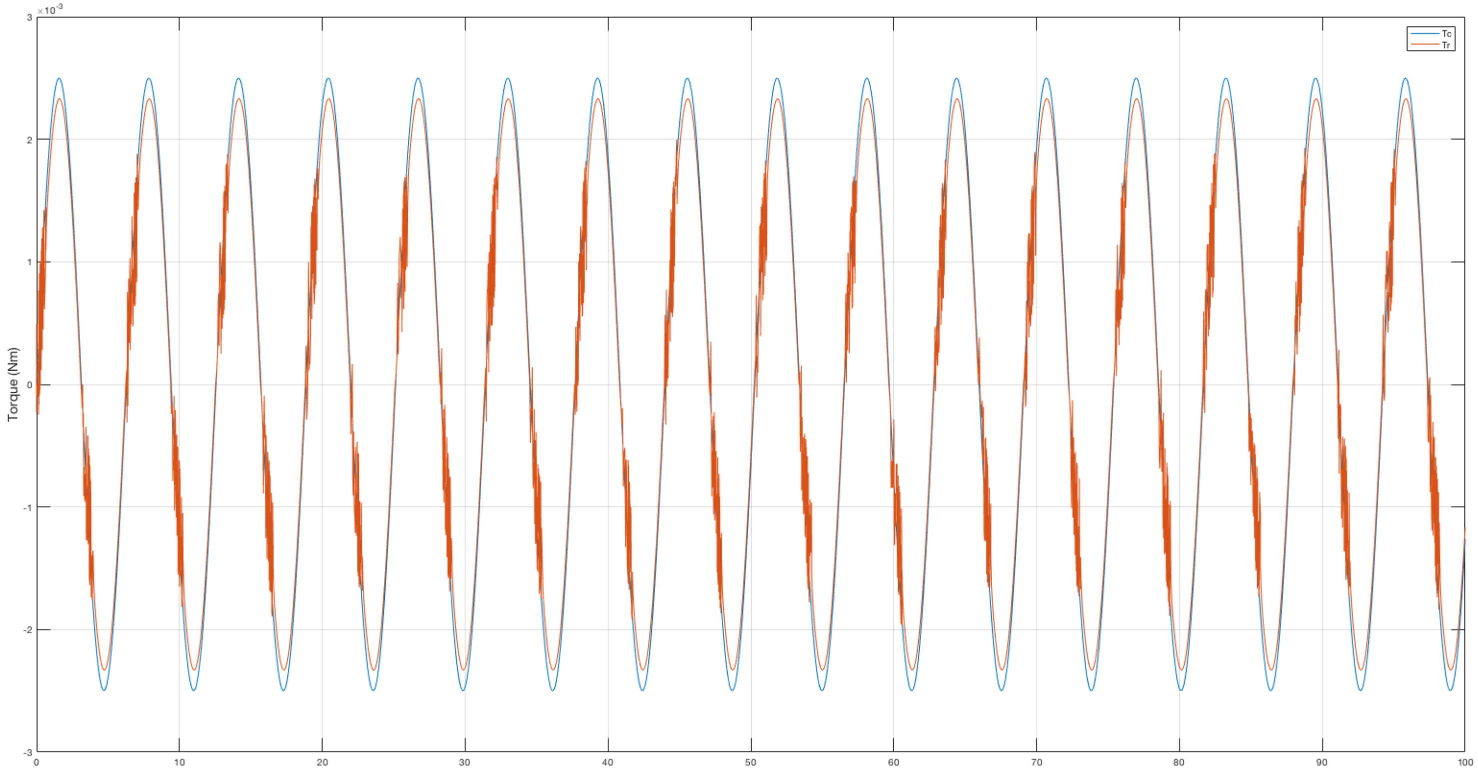
Angular speed

Motor current

Voltage

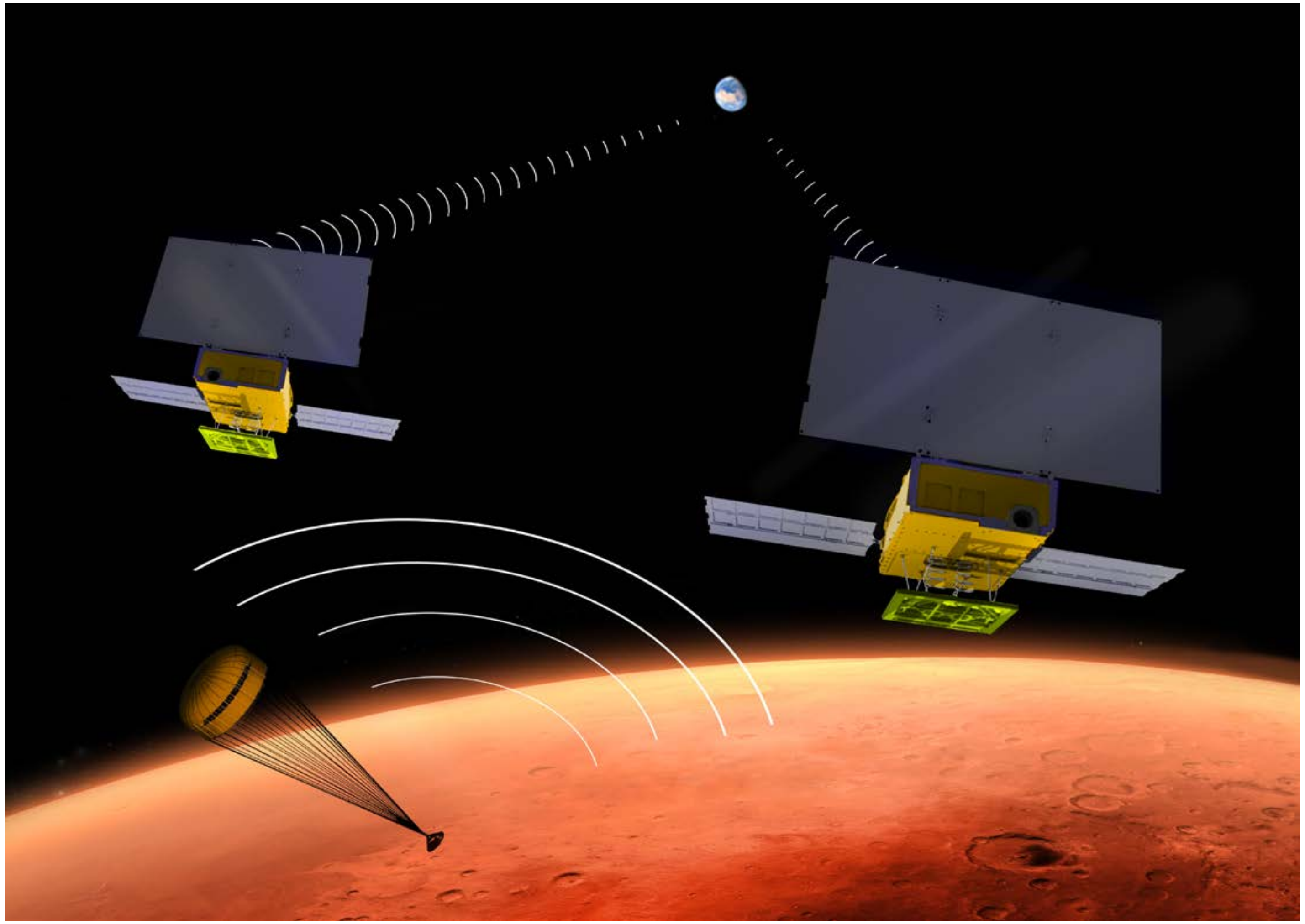

×10^-3
6
5
4
3
2
1
0
-1
-2
-3
-4
Torque (Nm)
0
10
20
30
40
50
60
70
80
90
100
Tc
Tr

# 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!

# Acknowledgements

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- Visiting Researcher
  - Zainab Saleem
- Student Intern
  - Elizabeth Torres de Jesus
- Tracie Conn
- Prognostics & Health Management Society

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