Fault Condition Modeling and Digital Twin Development for a Nuclear Thermal Propulsion System

Oak Ridge Institute for Science and Education — Shaping the Future of Science

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Background and Project Overview

- Nuclear Thermal Propulsion (NTP) utilizes nuclear reactors for in-space propulsion. Hydrogen acts as a coolant for the reactor and propellent for the rocket
- The National Aeronautics and Space Administration is funding this project to help safely and efficiently get humans to Mars

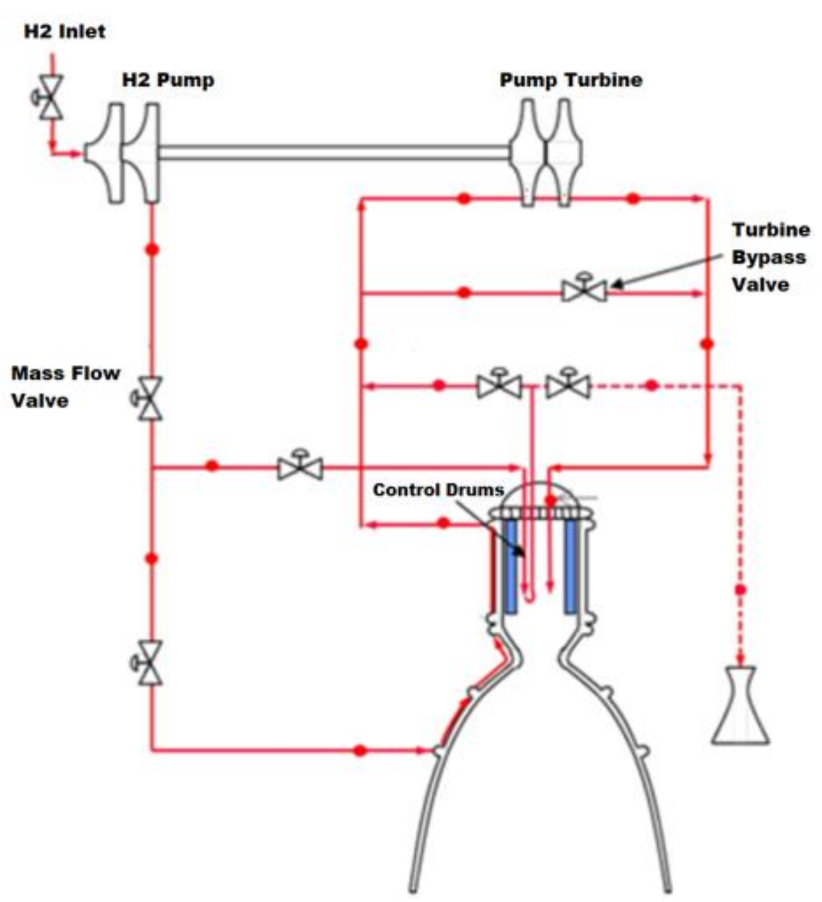

Fig. 1. Simplified NTP Diagram

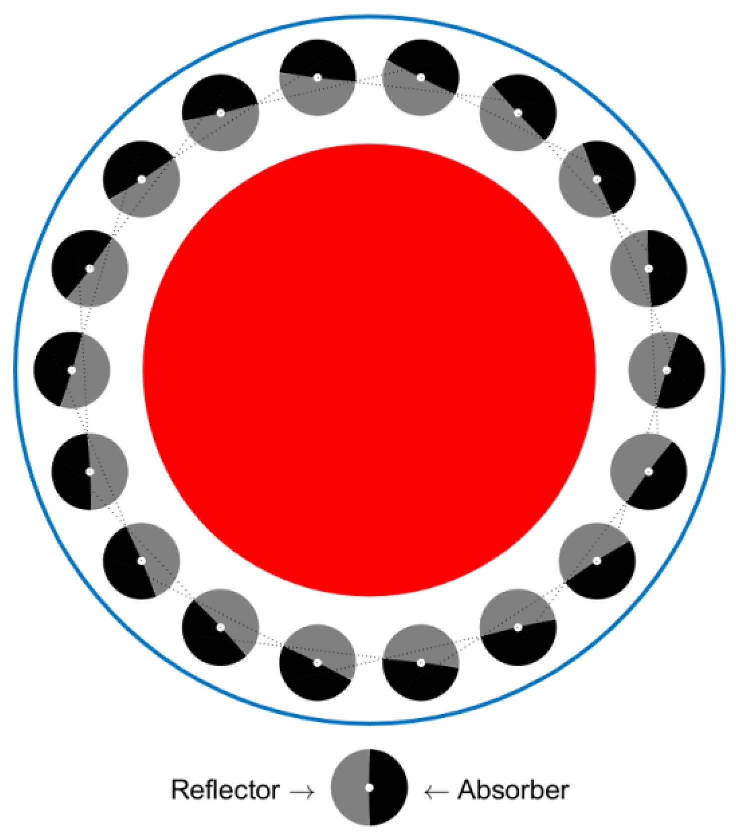

Fig. 2. Example control drum arrangement

- The reactivity within the nuclear reactor is managed via the control drums, which surround the core and are half absorptive, half reflective
  - The drums are rotated towards the absorptive material to slow the reaction, and vice versa
- Two fault modes were added the control drum system of an existing multi-physical dynamic model of the NTP system [1]
  1. Stuck drums
     - Drums stick in place after the initial thrust
  2. Resolver error
     - Error in angle measurement causes an abrupt change in drum position
- The NTP model is based in Modelica, using the ORNL developed TRANSFORM package [2]
- ORNL's NTP "mock-reactor" [3]
  - Physical two-loop flow system on campus
  - Will demonstrate fault conditions and various control strategies

Stuck-Drum Fault Mode

- Drums can "stick" in place for a variety of reasons during operation:
  - During operational transients, a mechanical failure in the drive could lead to an inability to move the drum
  - Once the reactor is at steady state (constant thrust), the drums move very little and could potentially freeze in place
- As seen in Fig. 3, as more drums are stuck, the available drums must make more extreme movements

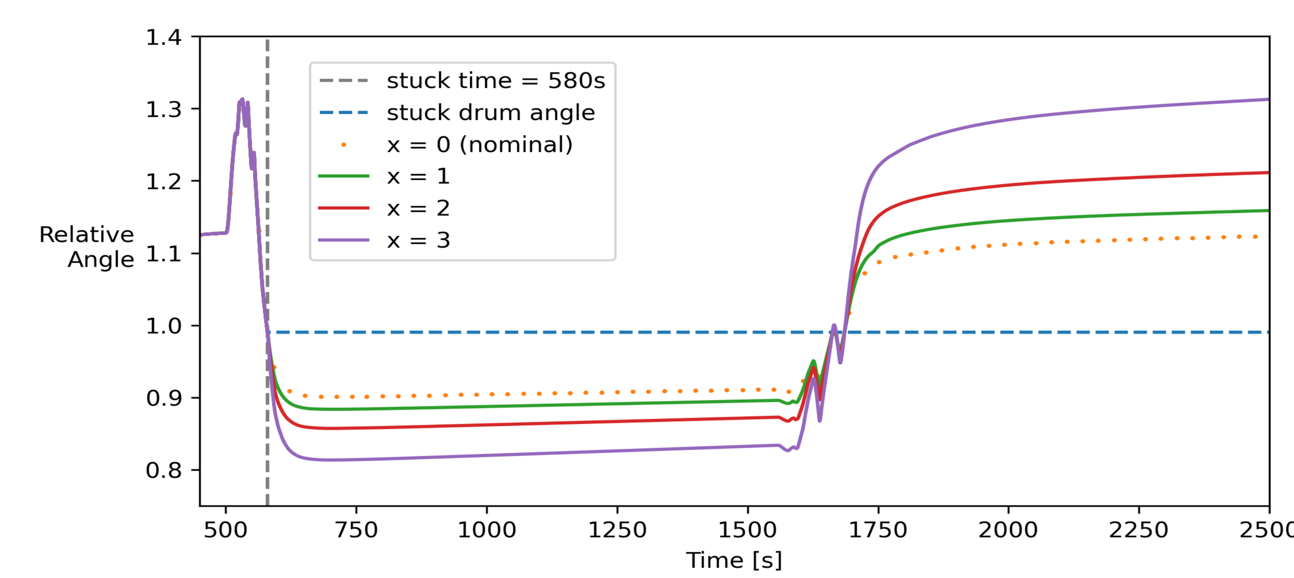

Fig. 3. Controller response for x number of stuck drums. Failure occurs at the gray vertical line at 580 s; the healthy response is indicated by the dotted orange line; the stuck angle is represented by the dashed blue line

Digital-Twin Development

- To help gain hands on experience with the instrumentation and controls (I&C) aspect of the NTP system, ORNL is creating a testbed for experimentation
- The two-flow system can be seen in Fig. 7; the loop of water will represent the cryogenic hydrogen and air will act as H2 gas

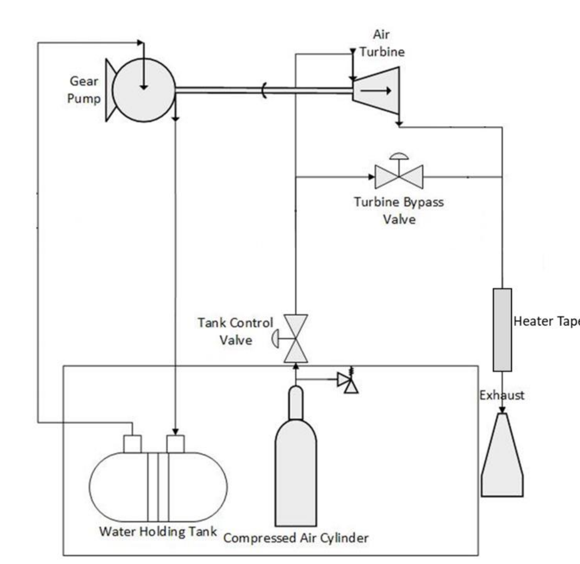

Fig. 7. Diagram of ORNL's NTP Mock-Reactor

- "Digital-Twin" of the Mock-Reactor has been modeled
- Concurrent simulation will take inputs from the physical system to control drum location and valve opening, as well as an equivalent heat input to provide to the heater tape (representing heating from the core)

Resolver Failure Fault Mode

- The resolver current individual angular position of the control drums
- An error in the drum feedback could lead to a quick change in the measured position of the drums

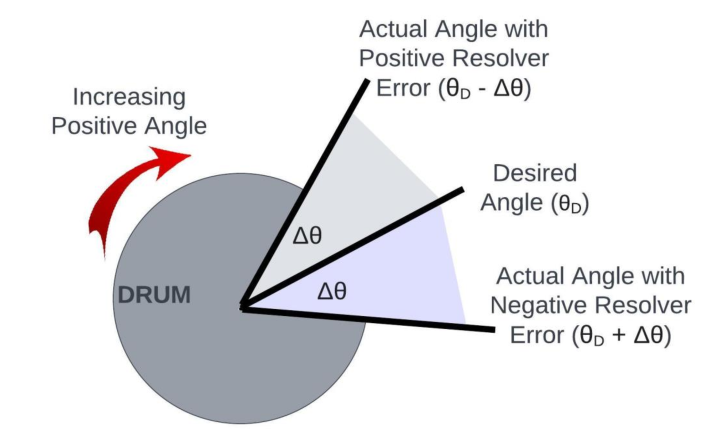

Fig. 4. Explanation of drum angle with positive and negative resolver error.

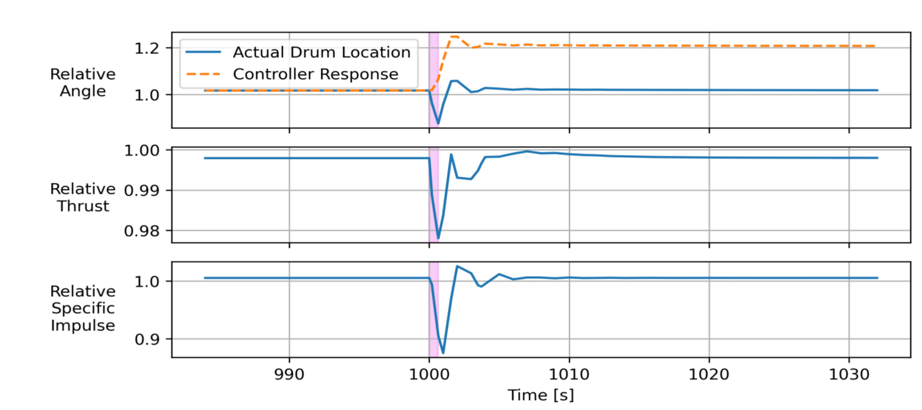

Fig. 5. System response to a positive resolver error.

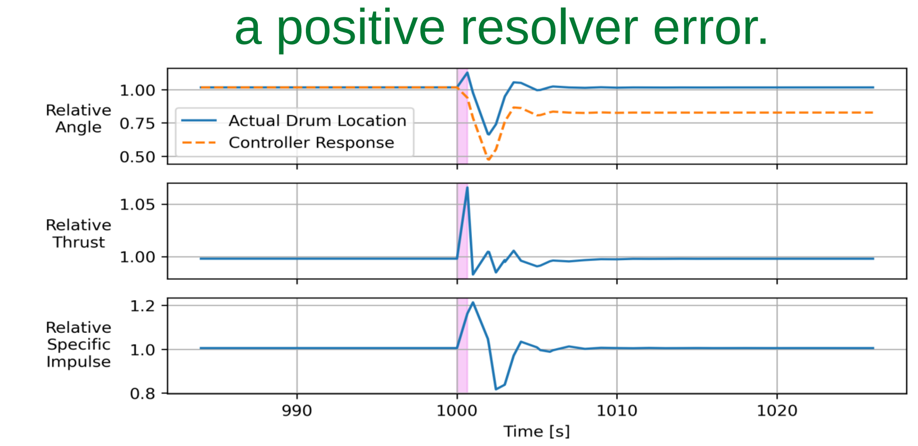

Fig. 6. System response to a negative resolver error.

- The system response to a positive and negative resolver error are shown in Fig. 5 and 6 respectively
- The rockets response (thrust and specific impulse) match closely to the relative drum location
- Model response closely resembles the results of our collaborators

Conclusions

- Modeling fault modes provides insight into potential issues which could occur during operation of an NTP rocket
- The system can respond to both modeled faults
- The mock-reactor provides a physical testbed for experimental I&C testing, for example adding a physical break to the mock reactor and cause a stuck drum

References

[1] J. D. RADER and M. B. R. SMITH, "Dynamic Nuclear Thermal Rocket and Engine Modeling, "Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting(2020).
[2] M. S. GREENWOOD, "TRANSFORM – TRANsient Simulation Framework of Reconfigurable Models" doi:10.11578/dc.20171025.2022.
[3] N. D. B. EZELL, B. WILSON, and W. WILLIAMS, "Non-Nuclear Instrumentation and Controls Demonstration Test Facility, "ANS Nuclear Emerging Technology for Space2023 Conference(2023).

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