COMPARISON OF ON-ORBIT MANUAL ATTITUDE CONTROL METHODS FOR NON-DOCKING SPACECRAFT THROUGH VIRTUAL REALITY SIMULATION

SPEAKER: GP CAPT AJIT KRISHNAN, DEPT. OF DESIGN AND MANUFACTURING

RESEARCH SUPERVISOR: PRADIPTA BISWAS

ABOUT ME

- NDA (1999-2002), AFA (2002-03)
- IAF fighter pilot (2003 –onwards)
- 2900 h of flying
  - ~ 2000 h on Su-30 MKI – Qualified on all roles, weapons, instructional
  - Rest on other aircraft
- Flying instructor since 2012
- Experimental test pilot since 2013
- Flight Commander of 30 Sqn (Su-30 MKI) Pune
- Astronaut trg – 2020 onwards
  - Captain and Flt Engr training on Soyuz MS at Star City Moscow
  - Mtech (Res) at IISc

CONTENT

Background

- Explanation of Terms
- Existing Spacecraft Cockpits
- Identification of Variations
- Summary of Manual Control
- Research Questions

Proposed Work

- VR Simulator
- Interfacing with Physical Devices
- User Study Design
- Results
- Conclusion

COMPARISON OF ON ORBIT MANUAL ATTITUDE CONTROL METHODS

FOR

NON DOCKING SPACECRAFT

USING

A VR SIMULATOR

- Ascent
- On Orbit
- Descent and Landing

COMPARISON OF ON ORBIT MANUAL ATTITUDE CONTROL METHODS

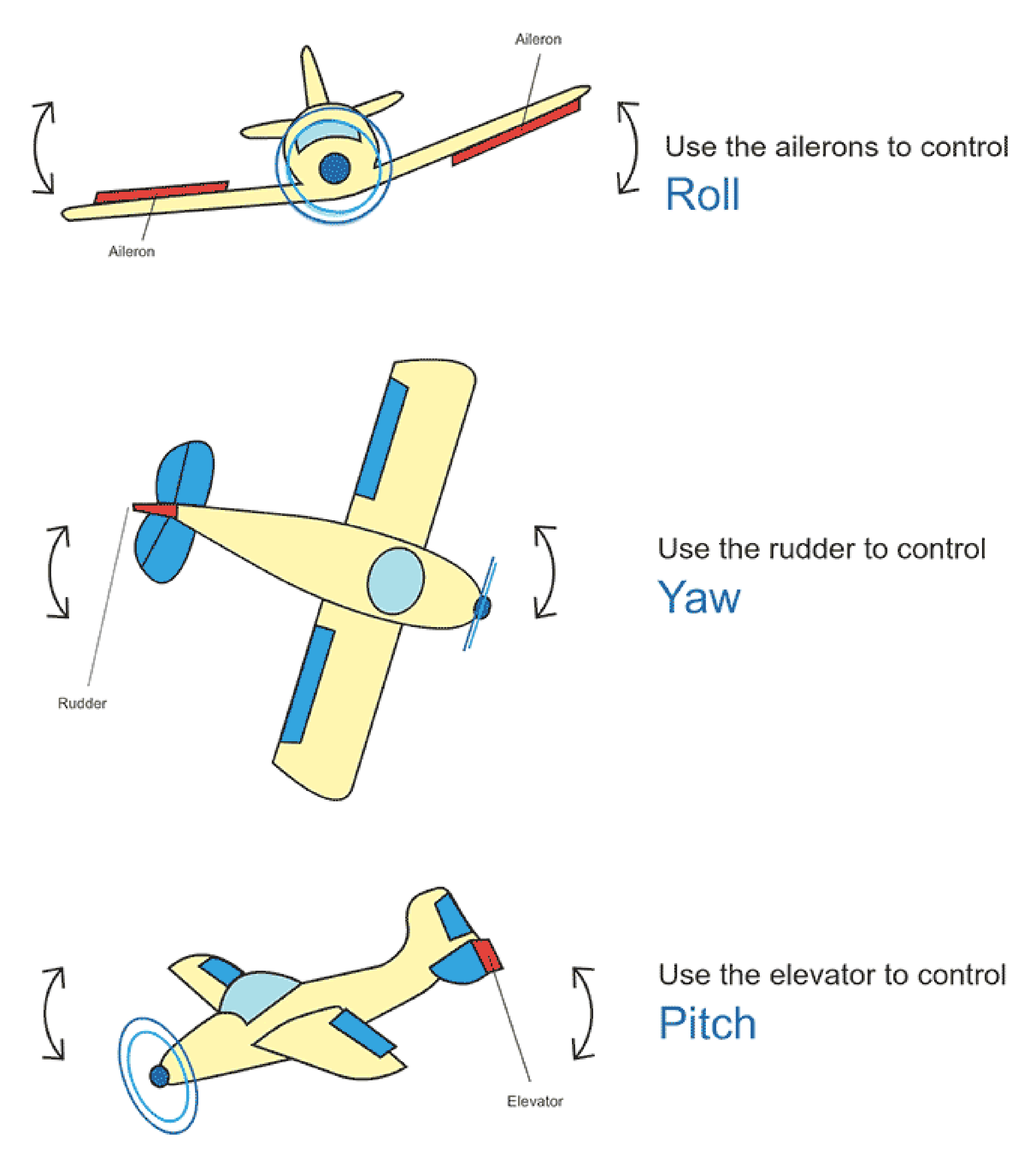
FOR

NON DOCKING SPACECRAFT

USING

A VR SIMULATOR

- Translation of Centre of Mass
- Rotation about Centre of Mass – Attitude Control
- Roll, Pitch and Yaw
- Attitude control is required for translation as well!
- Automatic, semi-automatic, manual


Aileron
Aileron
Use the ailerons to control
Roll
Rudder
Use the rudder to control
Yaw
Elevator
Use the elevator to control
Pitch

WHY MANUAL CONTROLS?

- NASA Human Rating standards - Mandatory
- Cater to unknown unknowns – unforeseen situations
- Dissimilar redundancy
- Fundamental element of crew survival
- Allows crew to bypass faulty/ failed automation
- Weight reduction
- All past, present and developmental manned spacecraft have it

COMPARISON OF ON ORBIT MANUAL ATTITUDE CONTROL METHODS

FOR

NON DOCKING SPACECRAFT

USING

A VR SIMULATOR

- Independent mission
- Doesn't join up and connect with another spacecraft/ space station

COMPARISON OF ON ORBIT MANUAL ATTITUDE CONTROL METHODS

FOR

NON DOCKING SPACECRAFT

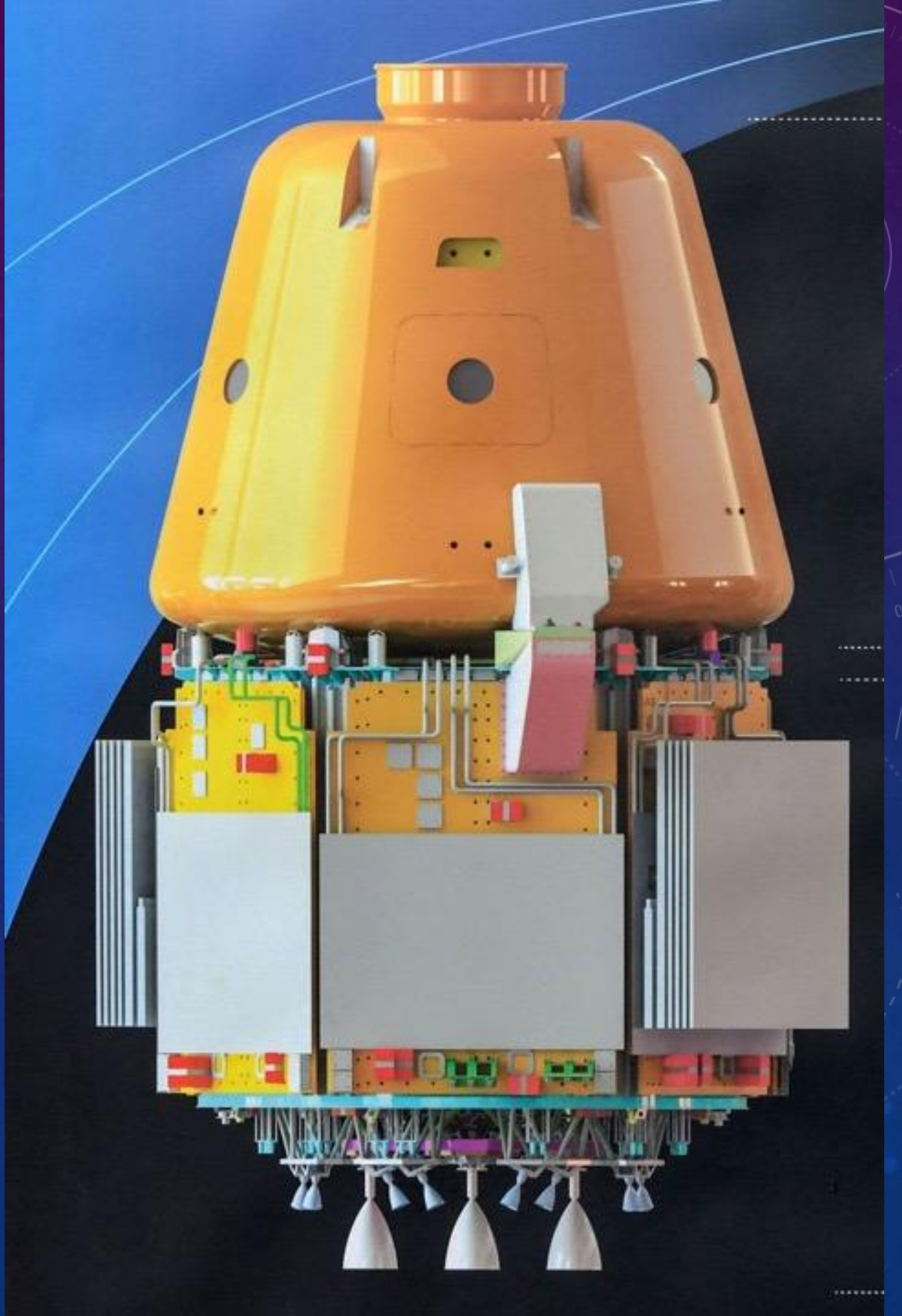
USING

A VR SIMULATOR

- Manned spacecraft distinct from an unmanned satellite

PROBLEM

- All manned spacecraft needs to be human rated (safe and operable by human crew)
- NPR (NASA Procedural Requirements) 8705.2c for Human Rating
  - Mandatory to have manual flight path control from insertion till parachute opening during descent
- Need a manual flight control simulator to demonstrate methods and concepts
- Different methods of manual control
- Which method should we follow?



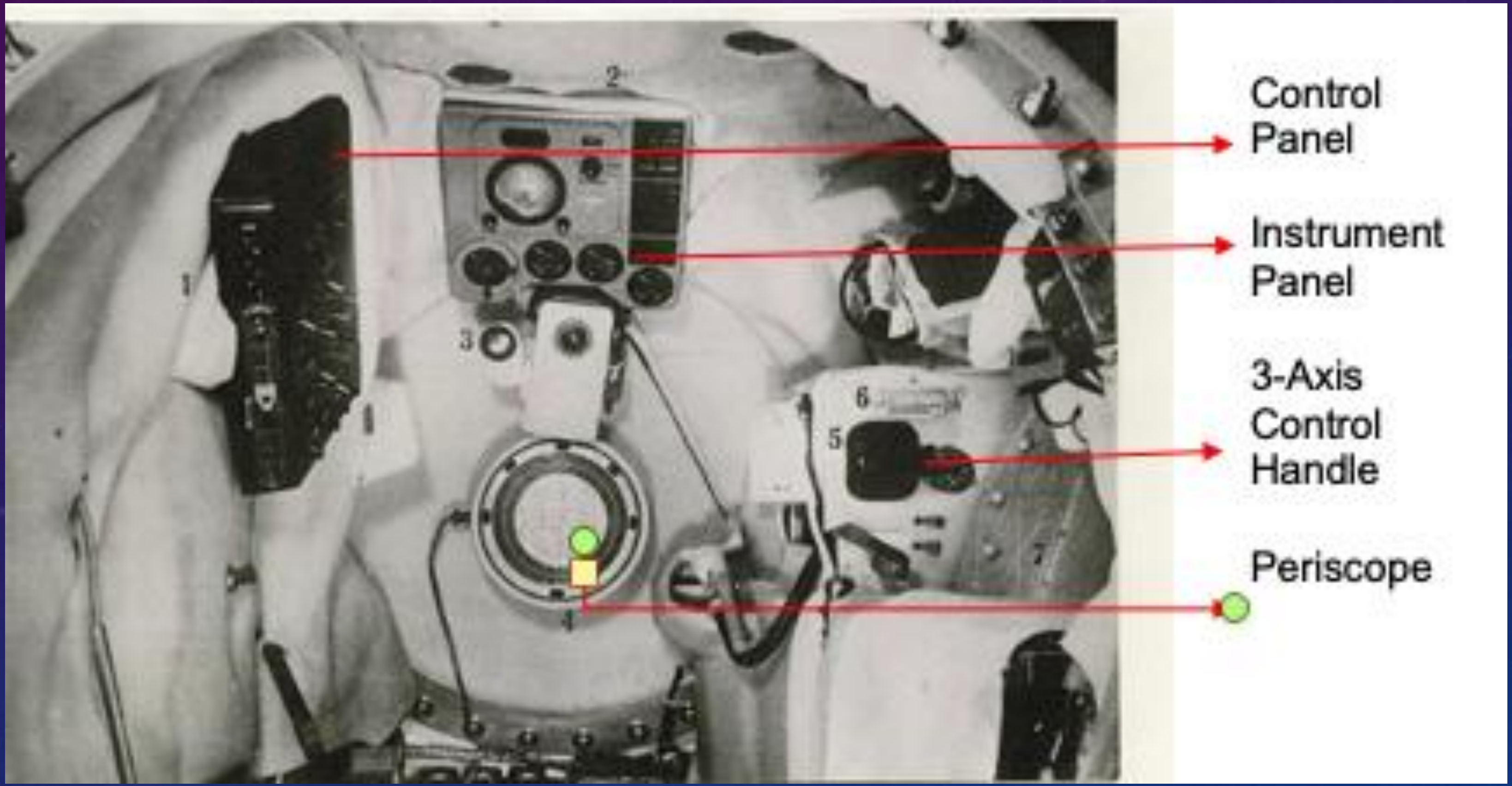
WHAT IS ATTITUDE FLYING?

- How do you know that you are sitting vertical on the chair?
- How do pilots know that their aircraft is flying straight and not inverted or banked?
- Horizon
- Actual and instrument horizon
- Is the horizon visible from space?

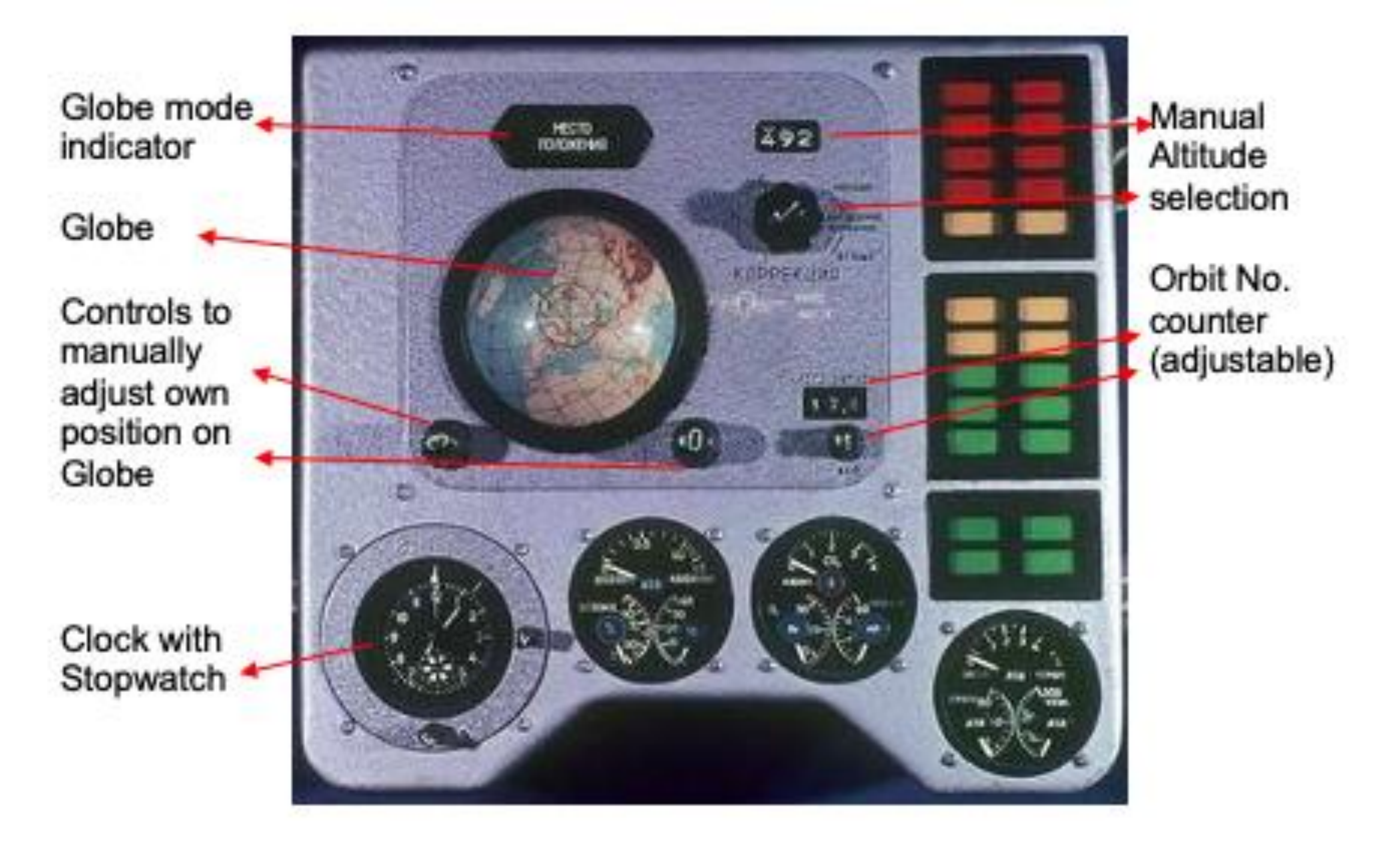
WHAT IS ATTITUDE FLYING?

- Is the horizon visible from space?
- Means to control attitude – 3 axis stick, touchscreen, buttons

VOSTOK/ VOSKHOD: EVEN YURI GAGARIN HAD IT



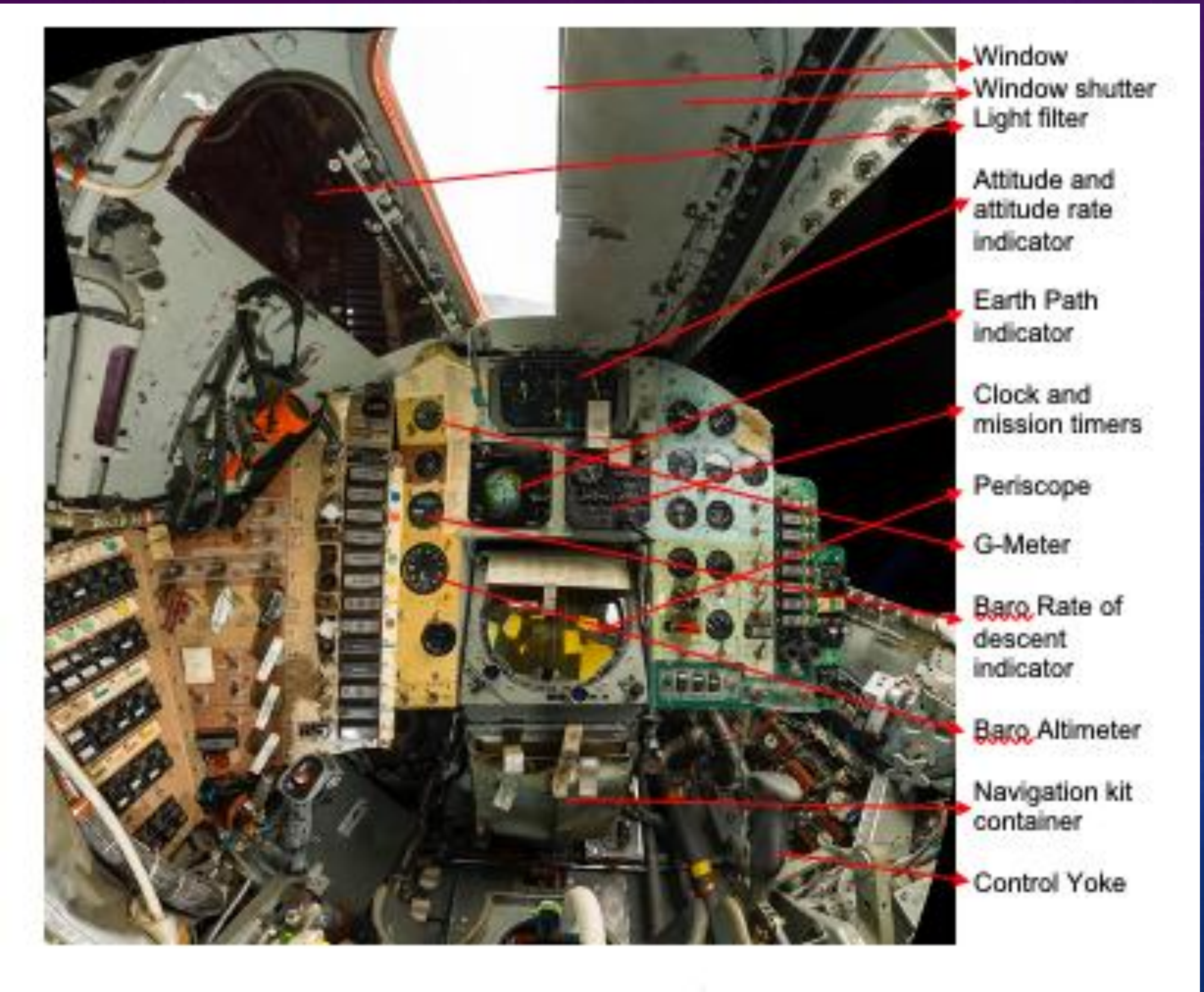
VOSTOK/ VOSKHOD: POSITION DISPLAY



VOSTOK/ VOSKHOD: PERISCOPE VIEW

VOSTOK/ VOSKHOD: CONTROL PANEL

MERCURY



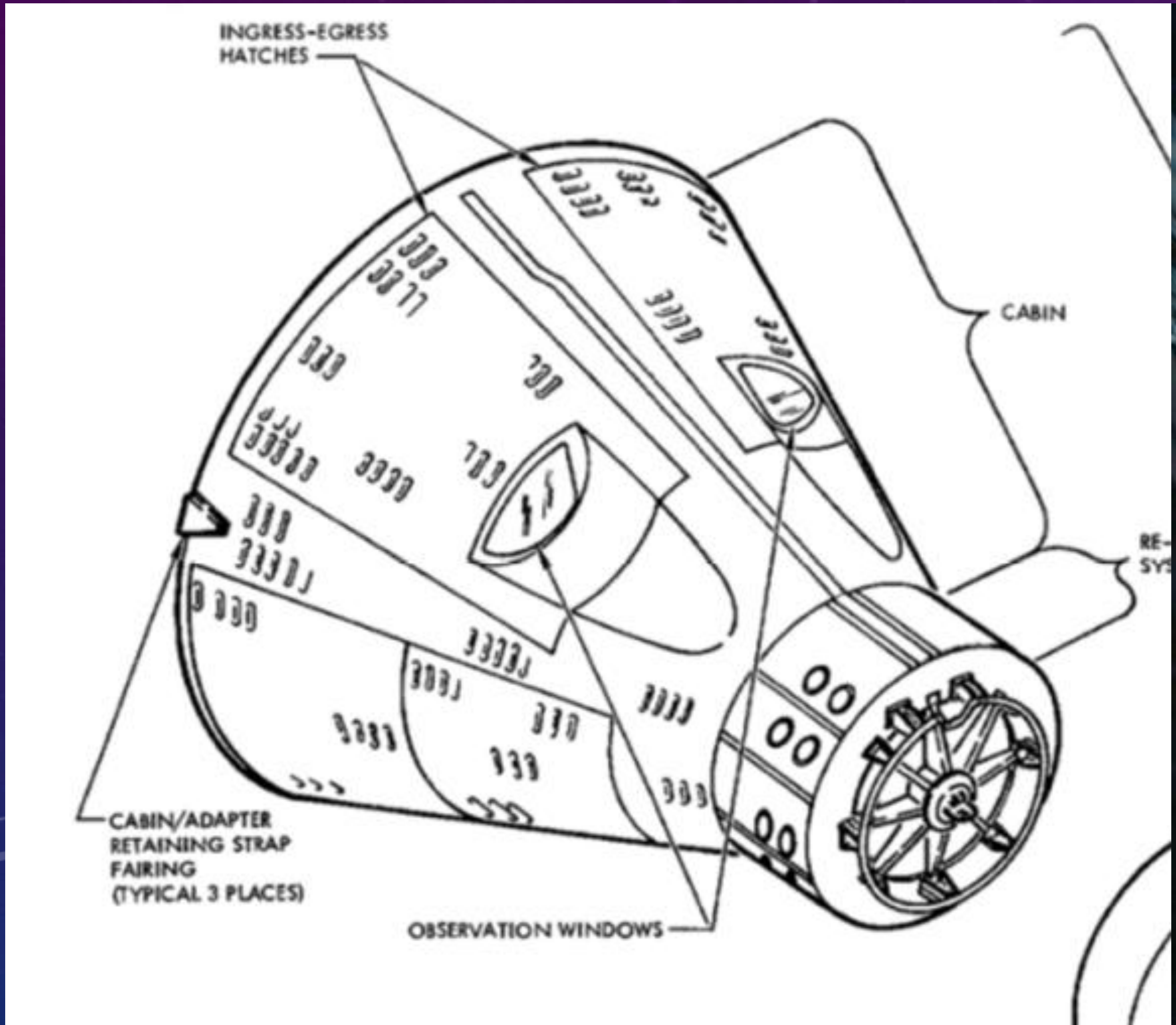
Window
Window shutter
Light filter
Attitude and attitude rate indicator
Earth Path indicator
Clock and mission timers
Periscope
G-Meter
Baro Rate of descent indicator
Baro Altimeter
Navigation kit container
Control Yoke

TIME
DEGREES
ORBIT

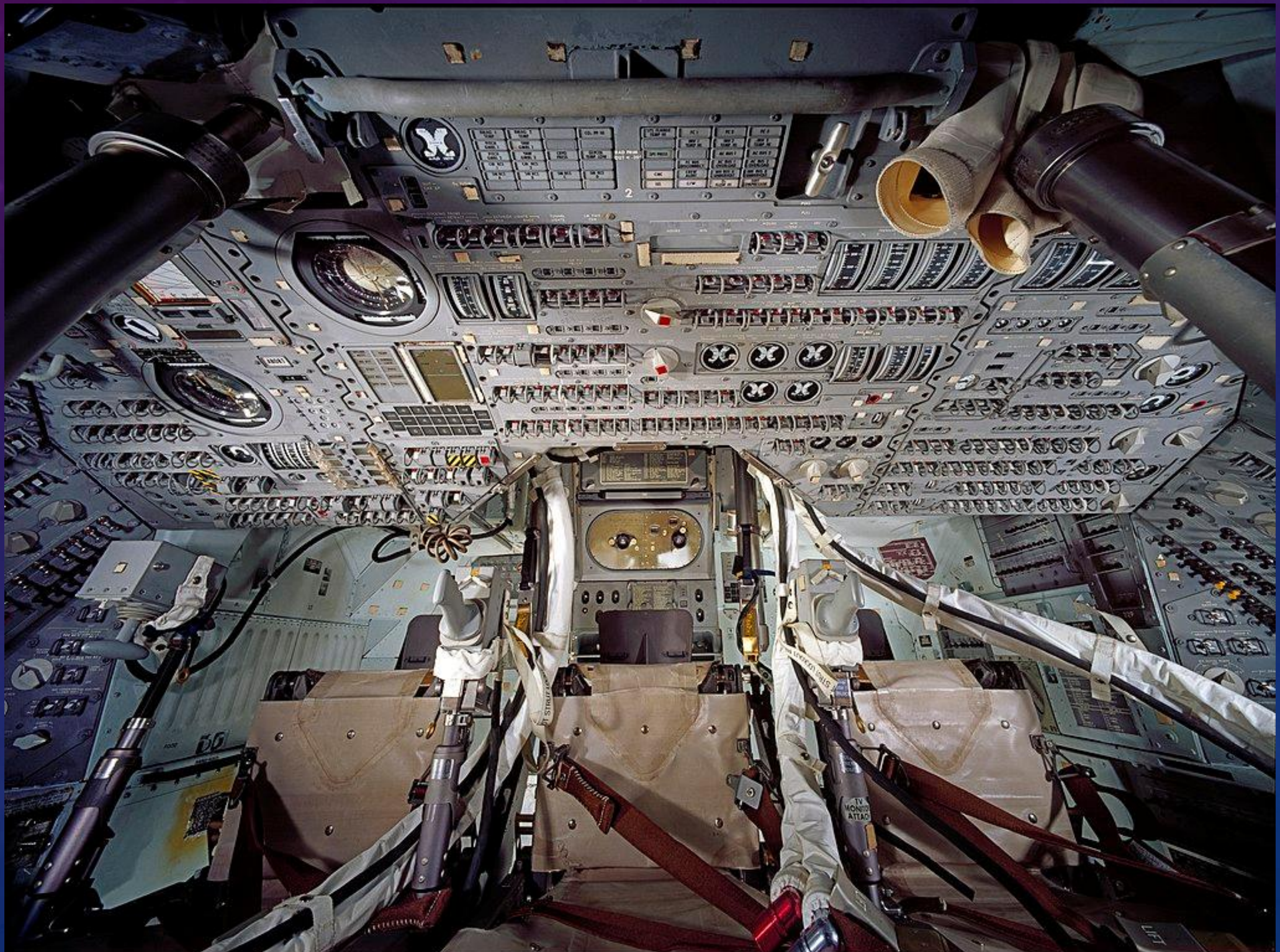
ORBIT
RETRO

GEMINI

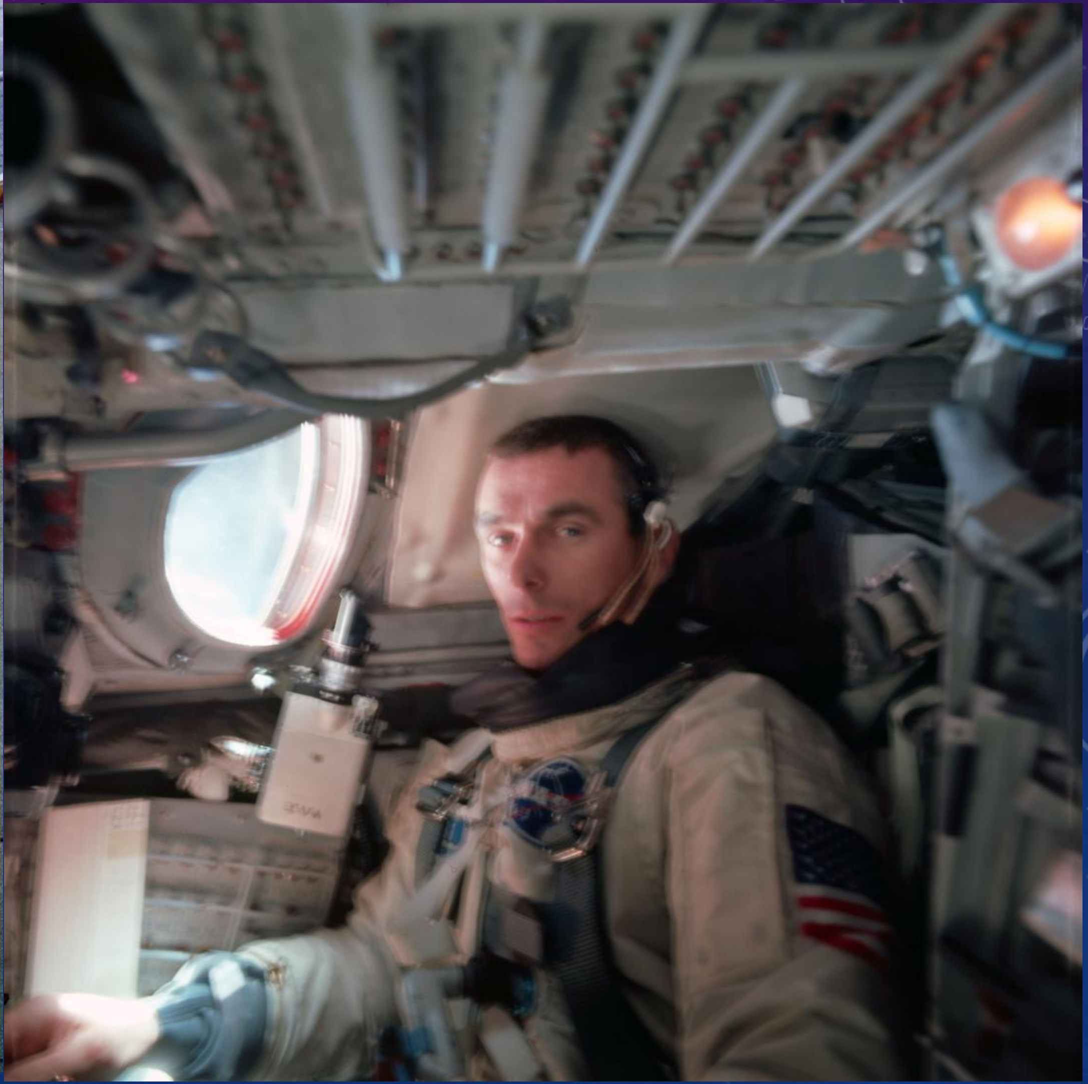
GEMINI WINDOWS



APOLLO



APOLLO WINDOWS

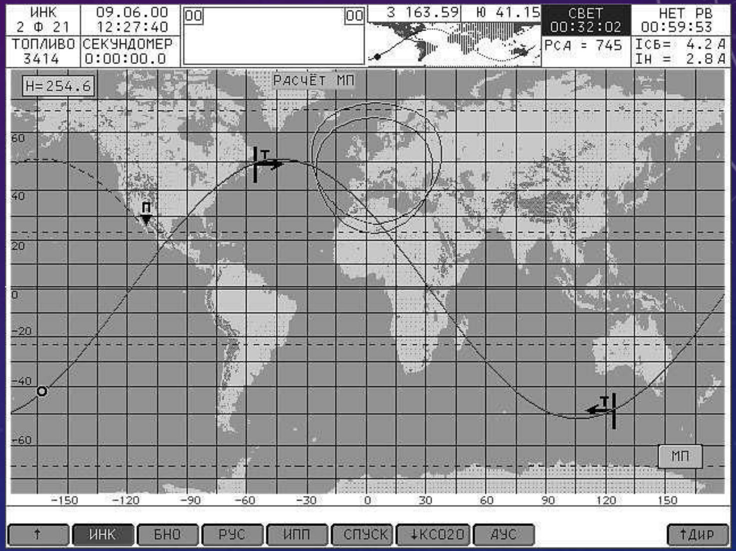


APOLLO ADI

ABORT
UPLINK ACTY
TEMP
NO ATT
GIMBAL LOCK
STBY
PROG
KEY REL
RESTART
OPR ERR
TRACKER
COMP ACTY
PROG
VERB
NOUN
VERB
NOUN
CLR
ENTR
RSET
KEY REL

SPACE SHUTTLE FLIGHT INSTRUMENTS

SOYUZ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IСБ= 4.2 А
IН = 2.8 А
РАСЧЁТ МП
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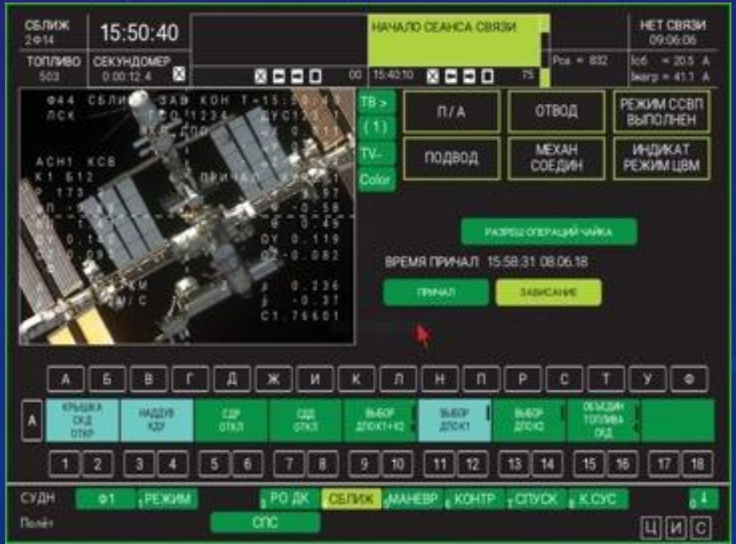
СБЛИЖ
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СЕКУНДОМЕР
П/А
ОТВОД
РЕЖИМ ССВП ВЫПОЛНЕН
ПОДВОД
МЕХАН СОЕДИН
ИНДИКАТ РЕЖИМ ЦВМ
ВРЕМЯ ПРИЧАЛ 15:58:31 08.06.18
СУДН
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СПУСК
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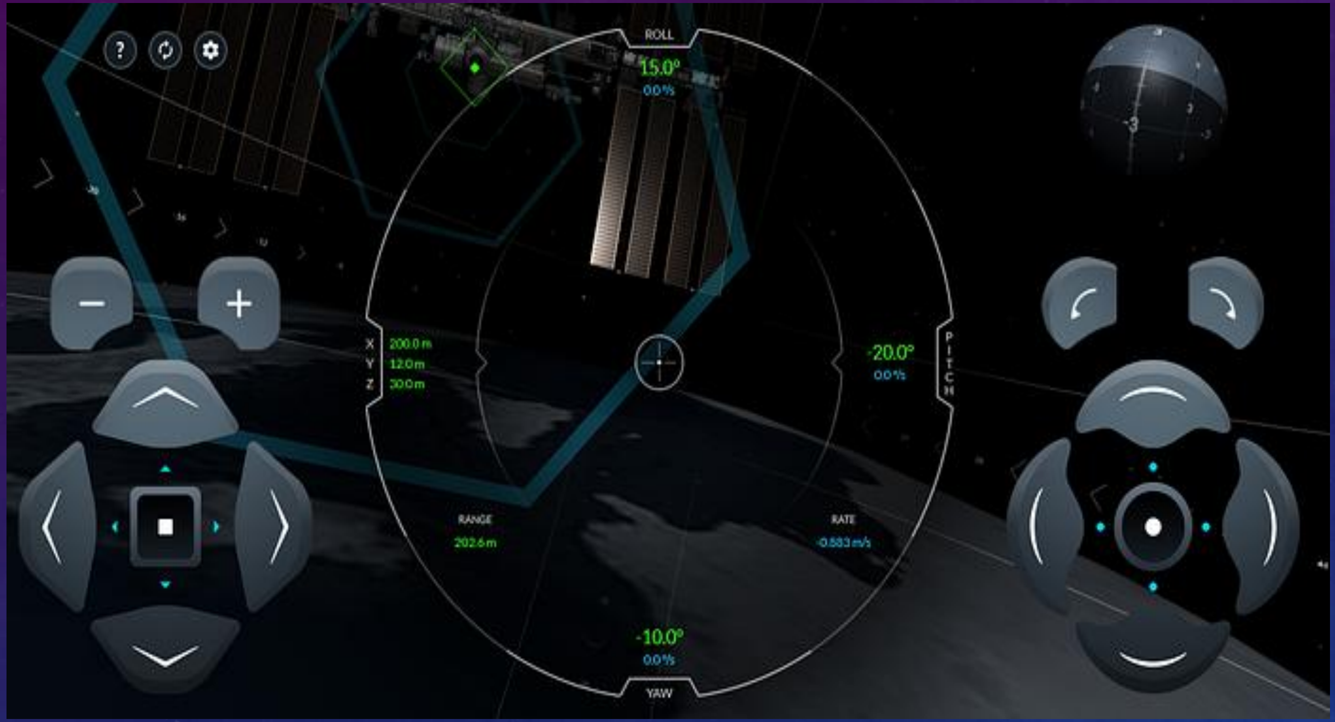
SHENZHOU

CREW DRAGON


ROLL
15.0°
0.0°/s
X 200.0 m
Y 12.0 m
Z 30.0 m
-20.0°
0.0°/s
PITCH
RANGE
202.6 m
RATE
-0.083 m/s
-10.0°
0.0°/s
YAW

BOEING STARLINER

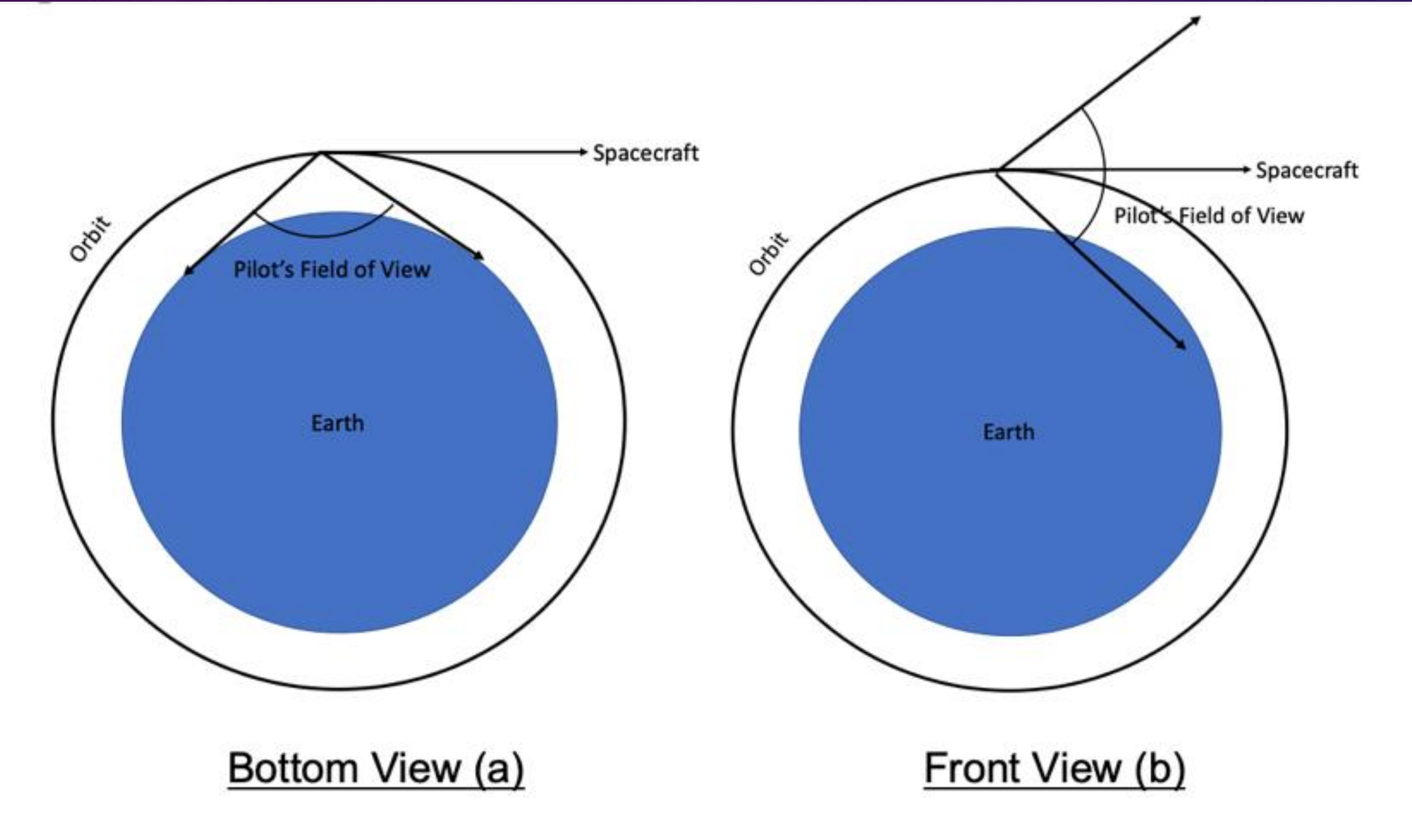
ORION

SUMMARY OF ON ORBIT MANUAL SPACECRAFT CONTROL

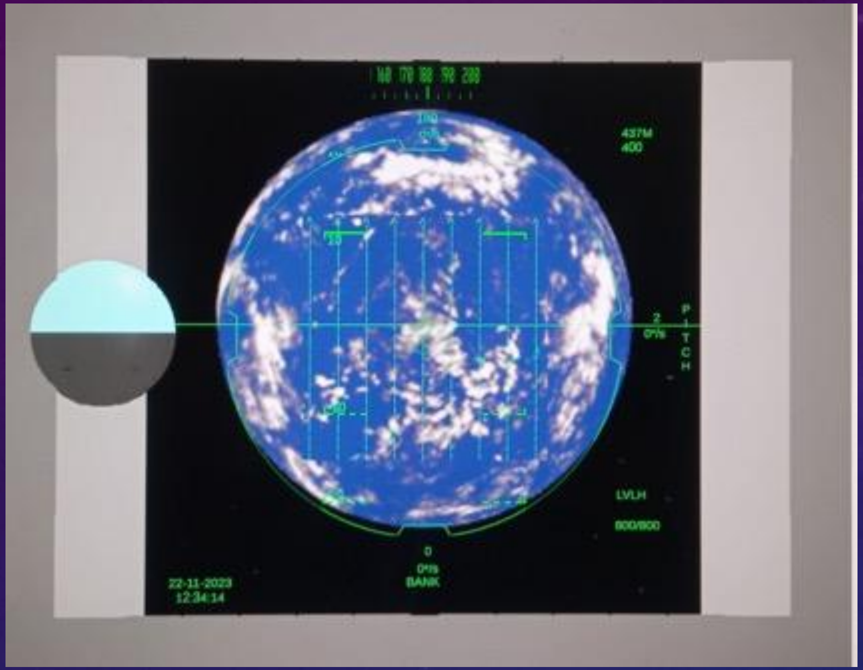
- On orbit manual attitude control available in all spacecraft
- On orbit manual translation control available in all docking spacecraft
- Visual reference aids
  - Front window, Periscope, Camera view (NASA)
- Periscope (Soyuz, Shenzhou)
- On orbit control method
  - 3 axis stick for attitude and translation
  - Knob type 3 axis stick in Soyuz
  - Touchscreen in Crew Dragon

PROPOSED RESEARCH

TWO TYPES OF EXTERNAL VIEWS



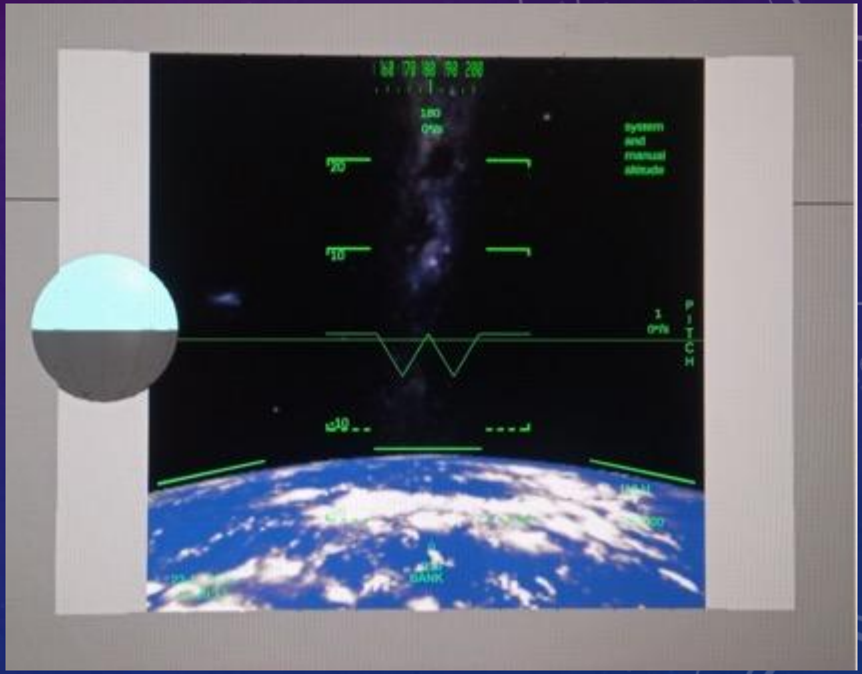
SPECIFIC AREAS OF STUDY IDENTIFIED



Bottom

vs

Front



3 axis control stick

vs

Keypad

vs

Touchscreen

HOW IS IT DONE IN OTHER SPACECRAFT?

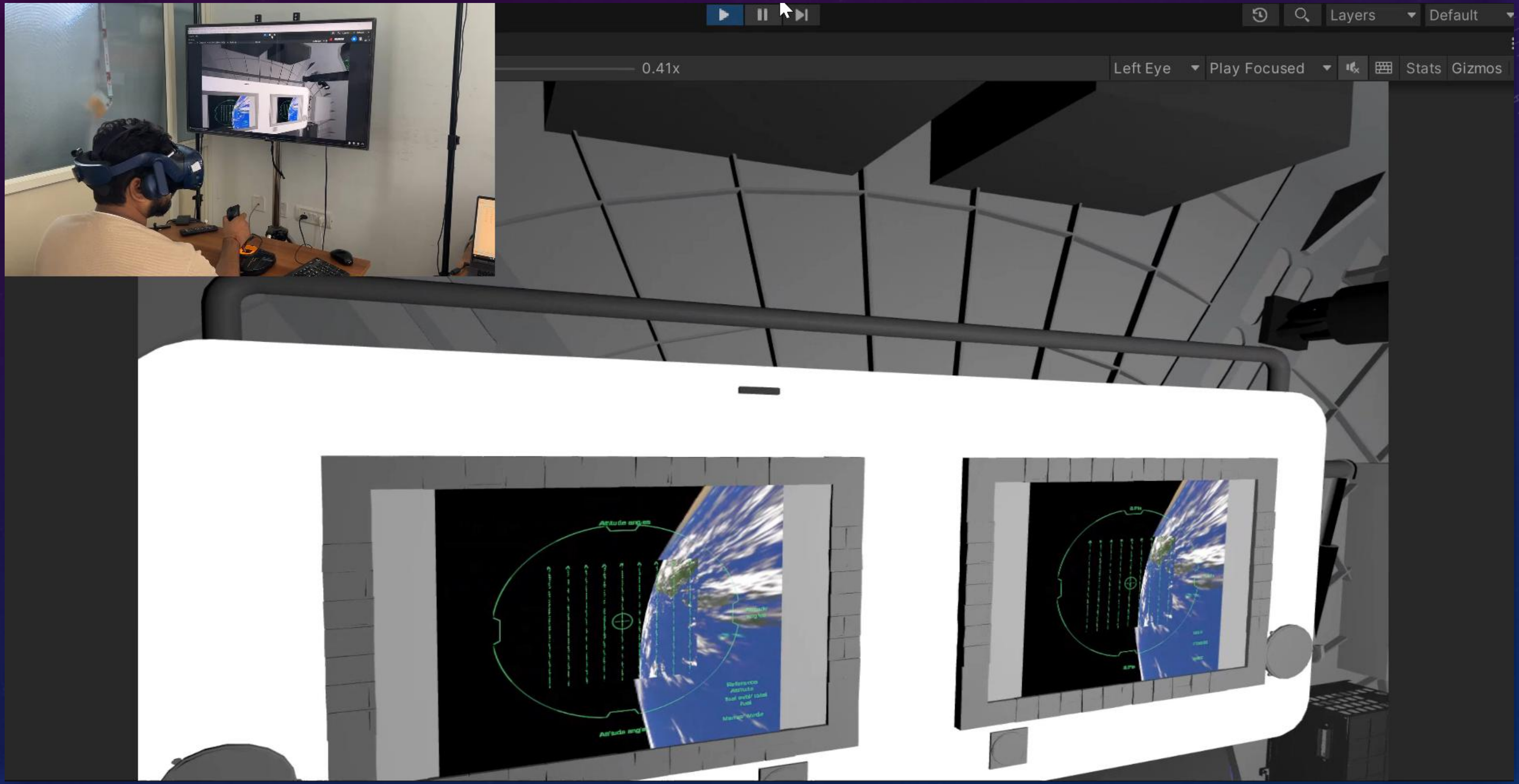
Spacecraft	External View			Control Method		
	Window	Camera	Periscope	3 Axis stick	Button	Touchscreen keys
Vostok	✓		✓	✓		
Voskhod	✓		✓	✓		
Mercury	✓			✓		
Gemini	✓			✓		
Apollo	✓			✓		
Soyuz	✓	✓	✓	✓	✓	
Shenzhou	✓	✓	✓	✓	✓	
Crew Dragon	✓	✓				✓
Orion	✓	✓		✓		
CST-100	✓	✓		✓		

QUESTIONS?

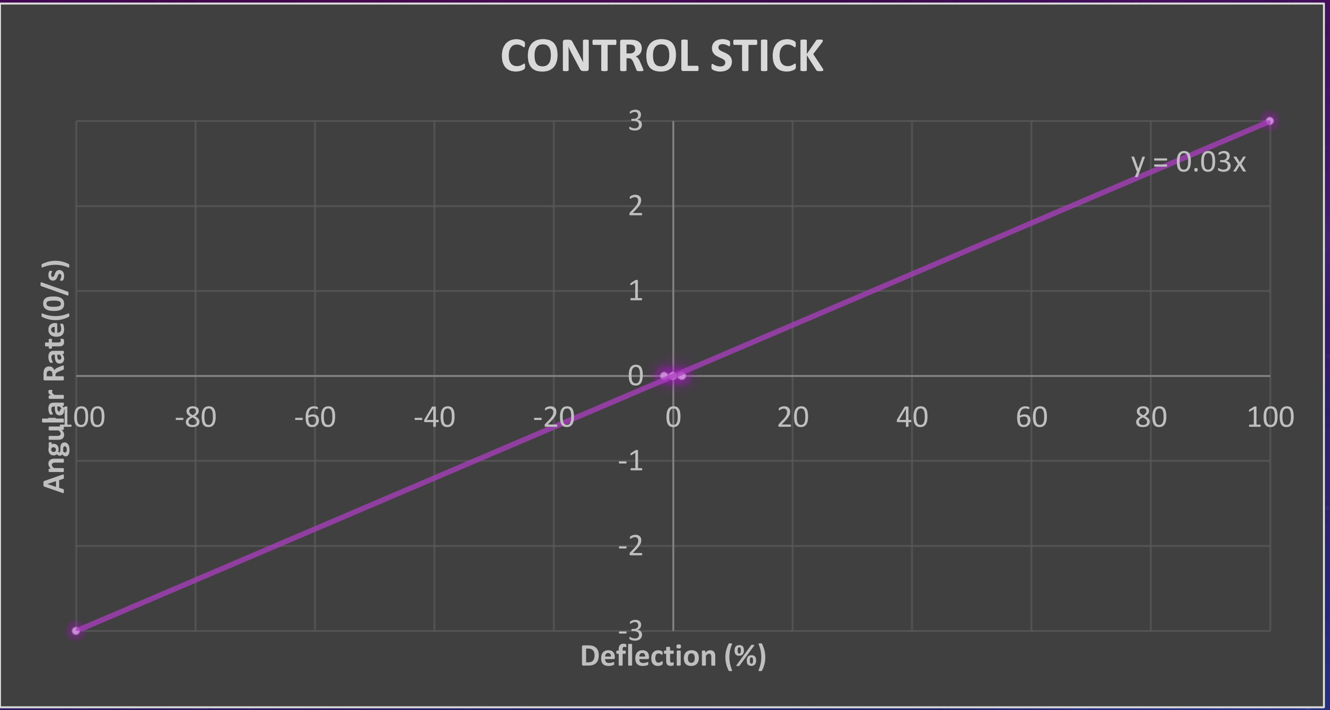
APPROACH

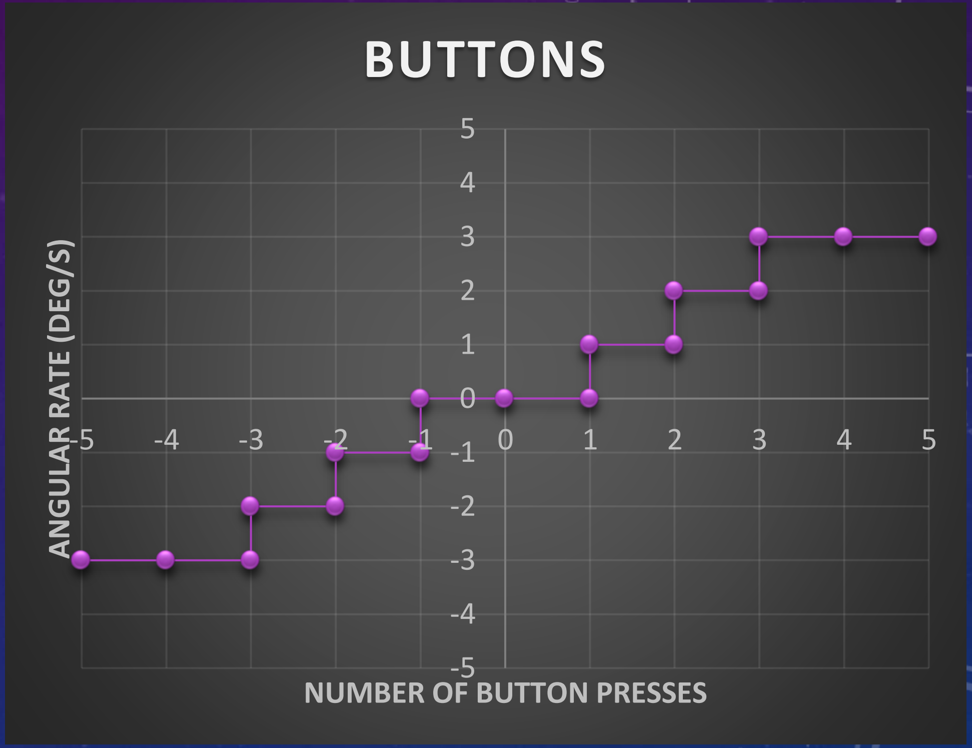
- Identify on-orbit manual flight control task– manual de-orbit
- Implement manual flight control schemes on a desktop simulator – UNITY VR based immersive visualization
- 3-D CAD model of spacecraft following Kepler's laws
- Camera view front and bottom on crew display panel
- Three axis stick, keypad (6 key) and touchscreen controls
- Restricting gloves
- User study to compare HMI
- Simulator can be integrated with 6DOF, CLAW optimization, camera options provided
- Flight instrumentation scheme – HUD type, ADI, task specific User Interface

VR SIMULATOR



CONTROL LAWS

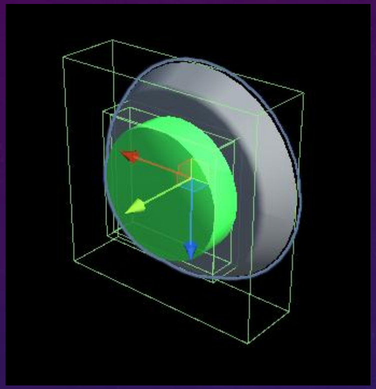


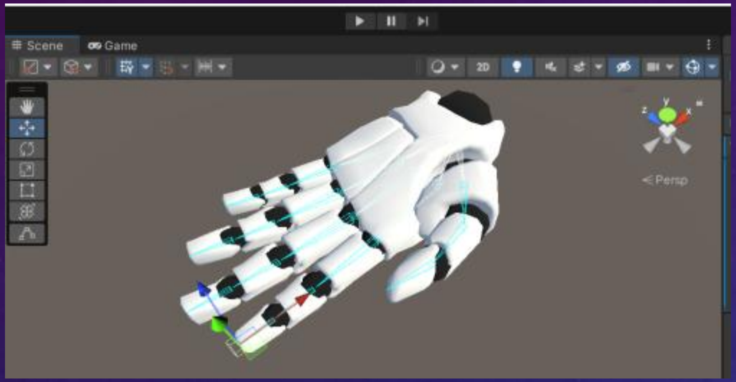


- Fuel Consumption

Delta angular rate => thruster firing => delta fuel consumed

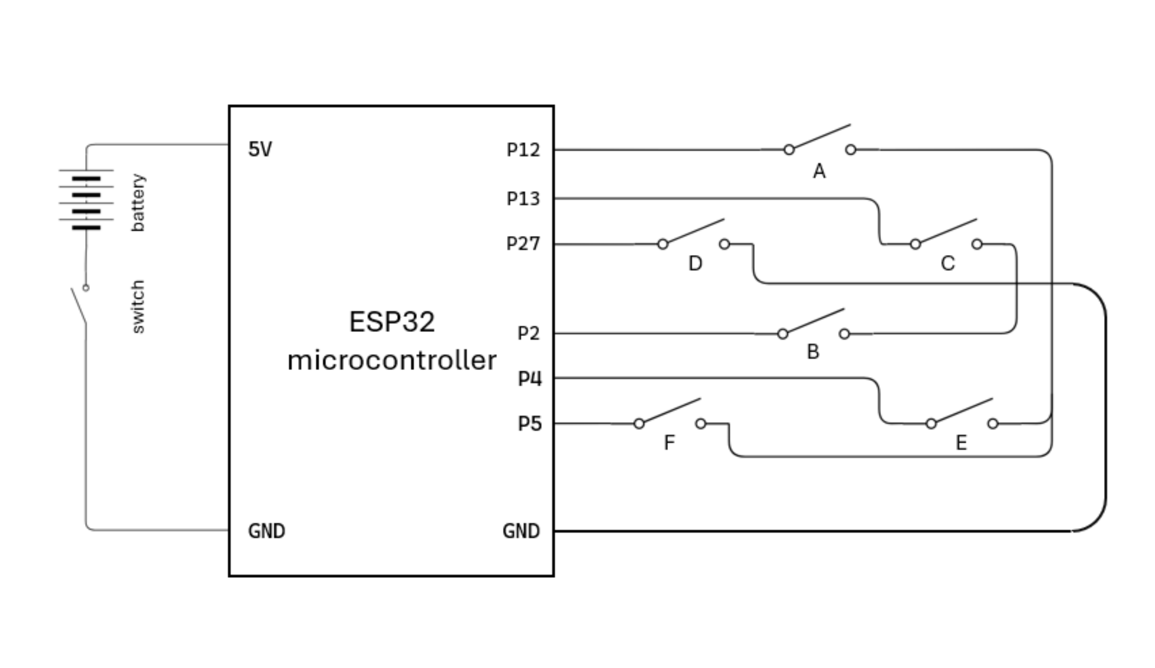
INTERFACING HAPTIC DEVICE

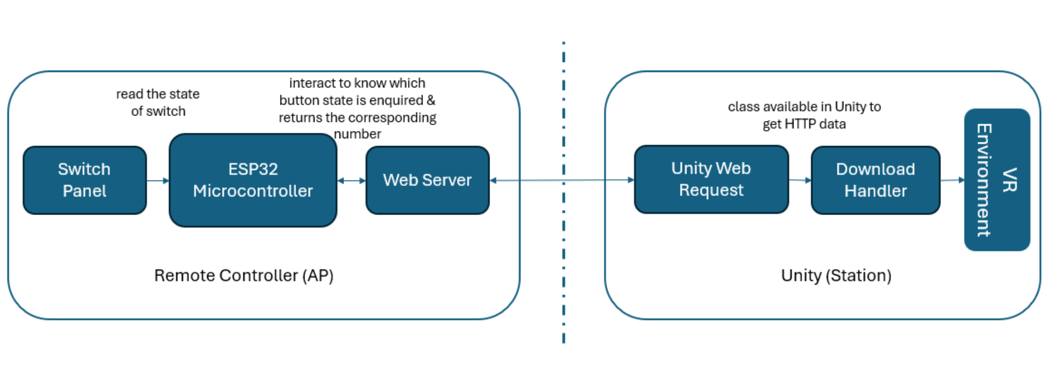


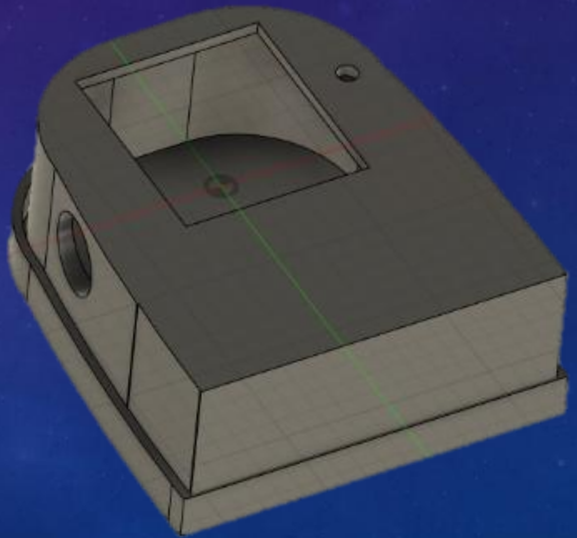


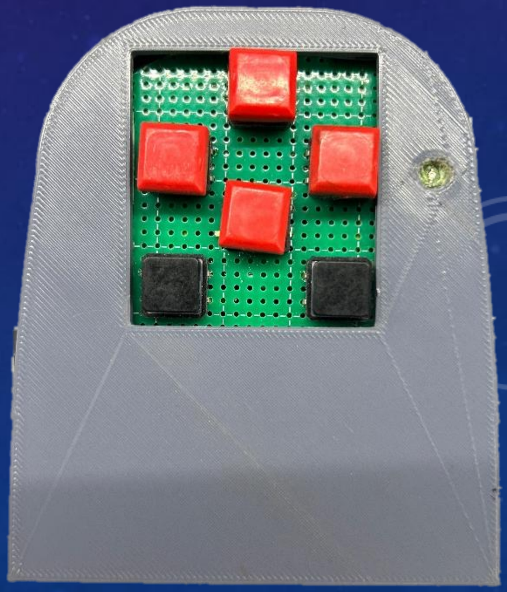
- Six Virtual Buttons mimic touchscreen buttons
- Vibration feedback
- Numeric feedback on display

BESPOKE SWITCH DESIGN









- Numeric feedback on display

EXPERIMENTAL TASK

- Initial attitude error wrt deorbit attitude:
  - Pitch 0º
  - Roll 102º
  - Yaw 104º.
- A portion of Earth was visible in either of the cameras.
- Task completion criteria:
  - Pitch $\pm$ 1º
  - Roll $\pm$ 1 º
  - Yaw $\pm$ 6 º

HUMAN FACTOR ANALYSIS

COGNITIVE LOAD ESTIMATION

- Finite capacity of working memory
- Mental workload

John Sweller


BBC NEWS

A mind-reading combat jet for the future

A demonstrator model of the Tempest is due to fly in 2027

By Michael Dempsey
Technology of Business reporter

During World War II, Spitfire pilots described their plane as so responsive it felt like an extension of their limbs.

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Kim Jong-un wants America's attention


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Indian military tests eye-tracking tech to help pilots control planes

TECHNOLOGY 12 June 2020
By Donna Lu

Eye-tracking devices could help pilots keep their hands on the throttle
Indian Institute of Science in Bangalore

Pilots in India are testing aircraft display systems that work by tracking and responding to eye movements and could let military pilots keep their hands on the plane's controls more often while flying.

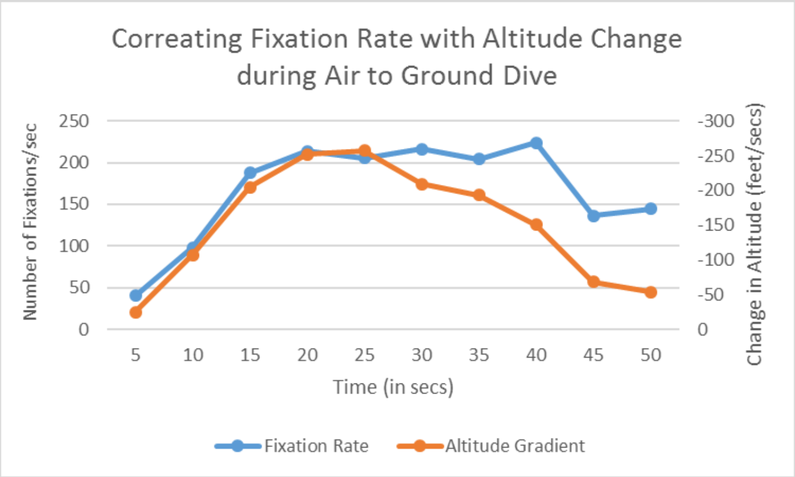
Modern aircraft have electronic display systems that show information such as the plane's fuel level, imaging system or geographical position. Pilots can click the screen to the relevant page of information as needed, but this requires taking one hand either off the plane's throttle or control ...

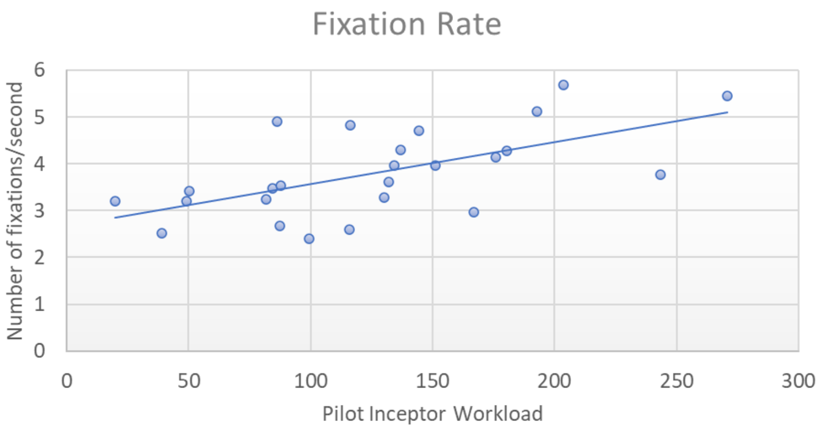
OCULAR PARAMETERS

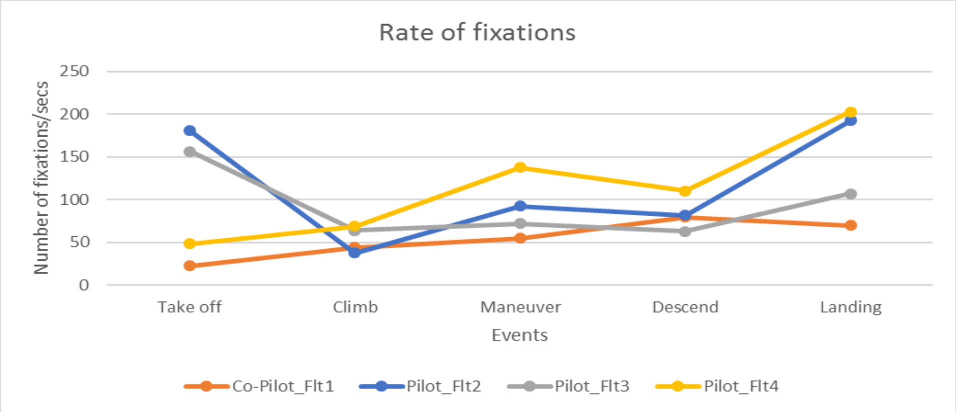
Indicator of Increased Cognitive Workload	
↑	Blink Duration
↑	Blink Interval
↑	Blink Frequency
↑	Saccade Rate
↑	Saccade Peak Velocity
↑	Saccade Amplitude
↑	Pupil Size
↑	Pupil Dilation
↑	Fixation Frequency
↑	Fixation Duration
↑	Horizontal Fixation
↑	Vertical Fixation
↑	Mean Dwell Time
↓	Saccade Extent
↓	Blink Rate
↓	Area of Visual Field

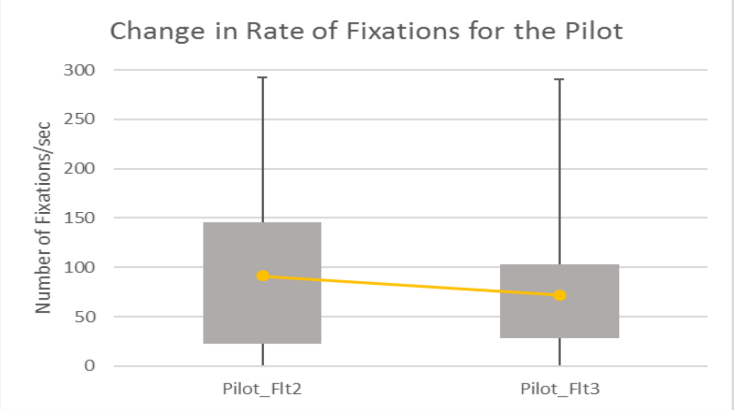
Melissa Patricia Coral, ANALYZING COGNITIVE WORKLOAD THROUGH EYE-RELATED MEASUREMENTS: A META-ANALYSIS, MS Thesis 2016
Wright State University

I3D



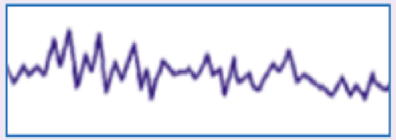
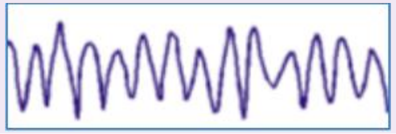






Previous Study @ I^{3}D Lab

EEG PSD ANALYSIS: FREQUENCY BANDWIDTHS

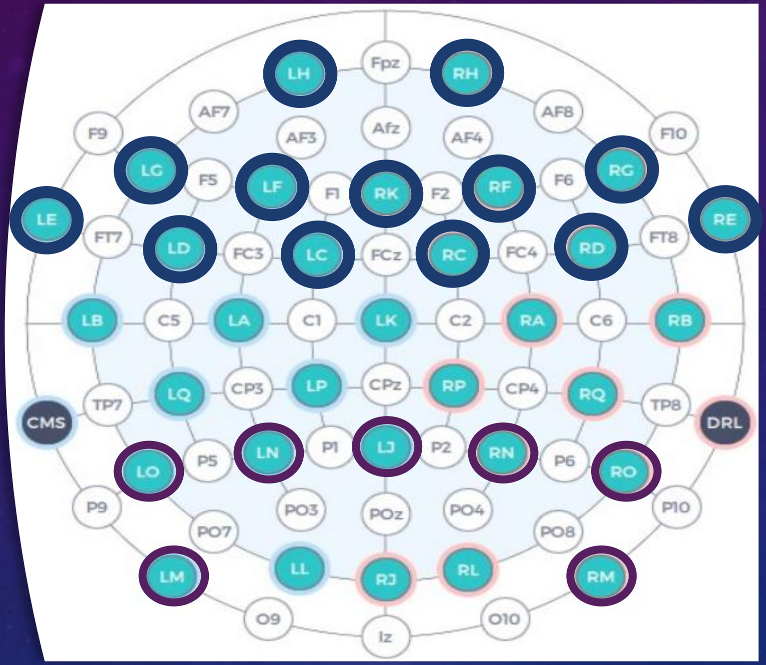
	Band	Frequency (hz)	Correlates
	Delta	<3	Slow wave sleep
	Theta	3-7	Memory Creation, Hypnagogia
	Alpha	8-13	Relaxation, Reflection Closed Eyes, Intrinsic Focus
	Beta	13-30	Active cognition, Intense concentration
	Gamma	30+	Multisensoring processing, Euphoria, High Focus
	Mu	8-12 (Over sensorimotor)	Suppression has been linked with empathy

PSD ANALYSIS

TASK LOAD INDEX

θ/α

ENGAGEMENT INDEX



$$\frac{\beta}{a+\theta} \qquad \frac{\beta}{\alpha} \qquad \frac{1}{\alpha}$$

USER STUDY DESIGN

Three User Studies

- Pilot Study : VR vs 2D Interface involving students
- Study 1: View and Manoeuvre interface comparison
    - View Orientation
        - Bottom View vs Front View
    - Manoeuvre Interface
        - Flight Stick vs Physical Buttons vs Virtual Buttons
    - 6 test pilots and 6 civilians
- Confirmatory Study 2: Comparing View Orientation
    - Bottom View vs Front View
    - 6 test pilots and 6 civilians

List of Instruments

- HTC Vive Pro Eye – VR Headset with integrated Tobii Eye Tracker
- Emotiv 36 channel EEG Tracker
- Emotiv EEG Data Analysis Suite
- Thrustmaster 3 DoF Flight Stick
- Manus Haptic Gloves
- Cambridge EDC Inclusive Design Toolkit for Space suite simulation
- Bespoke VR Software
- Bespoke Physical Switch

FACTORS USED FOR COMPARISON

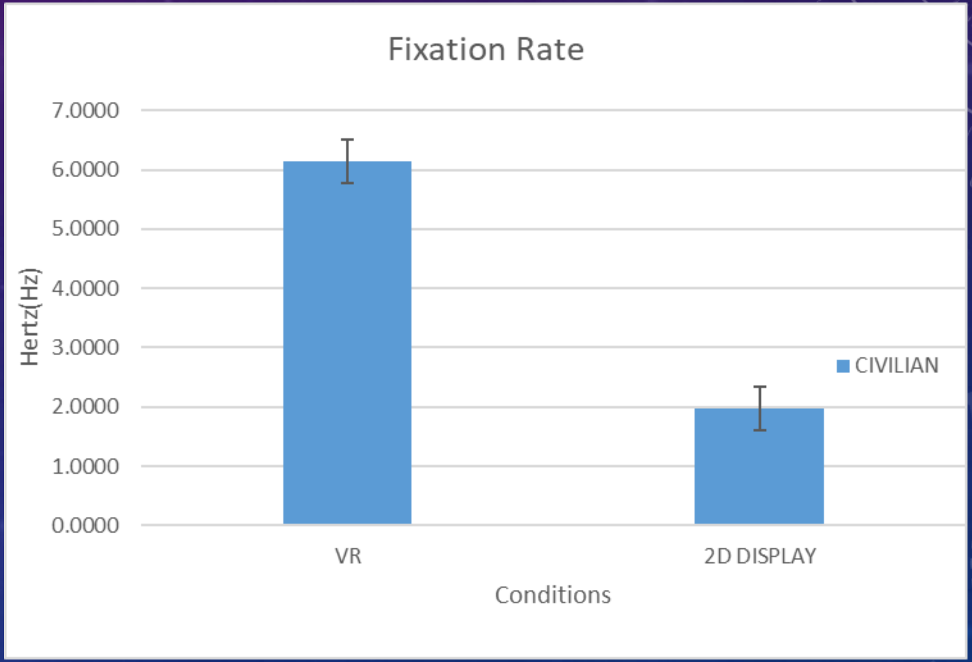
- Flight Parameters
  - Time Taken
  - Fuel Consumed
- Cognitive Load through Human Factors
  - Ocular Parameters
  - EEG PSD – Task Load Index, Engagement Index
- Questionnaires
  - IBM System Usability Score (IBM SUS)
  - NASA Task Load Index (NASA TLX)

RESULTS – VR VS 2D SCREEN COMPARISON

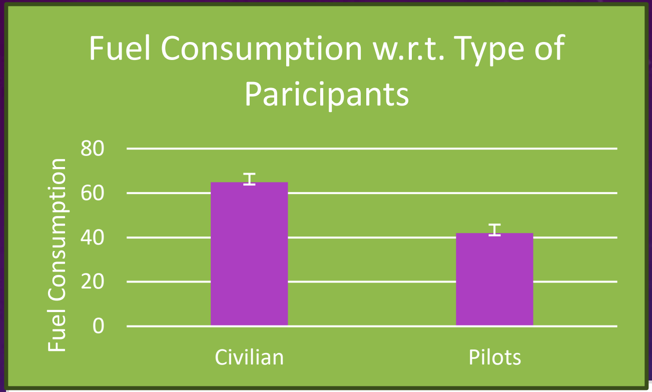
- Significant difference between VR and 2D display on the variable Fixation

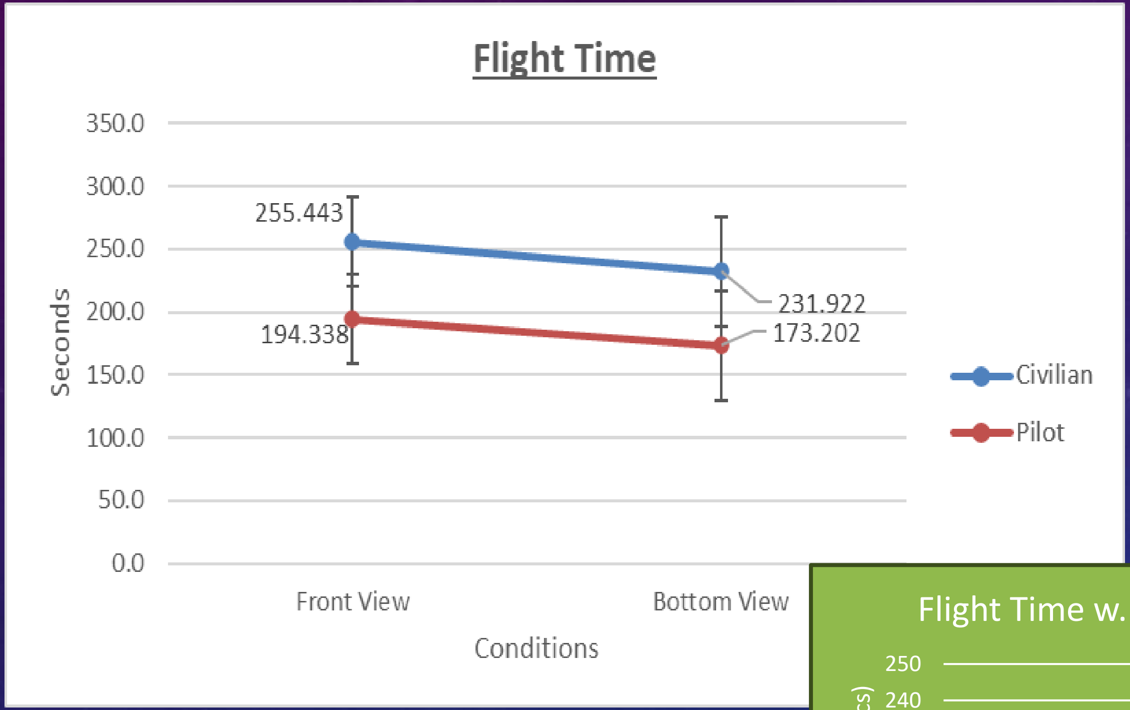
Rate (t(7) = 8.215, p = 0.00, Cohen's d = 2.442).

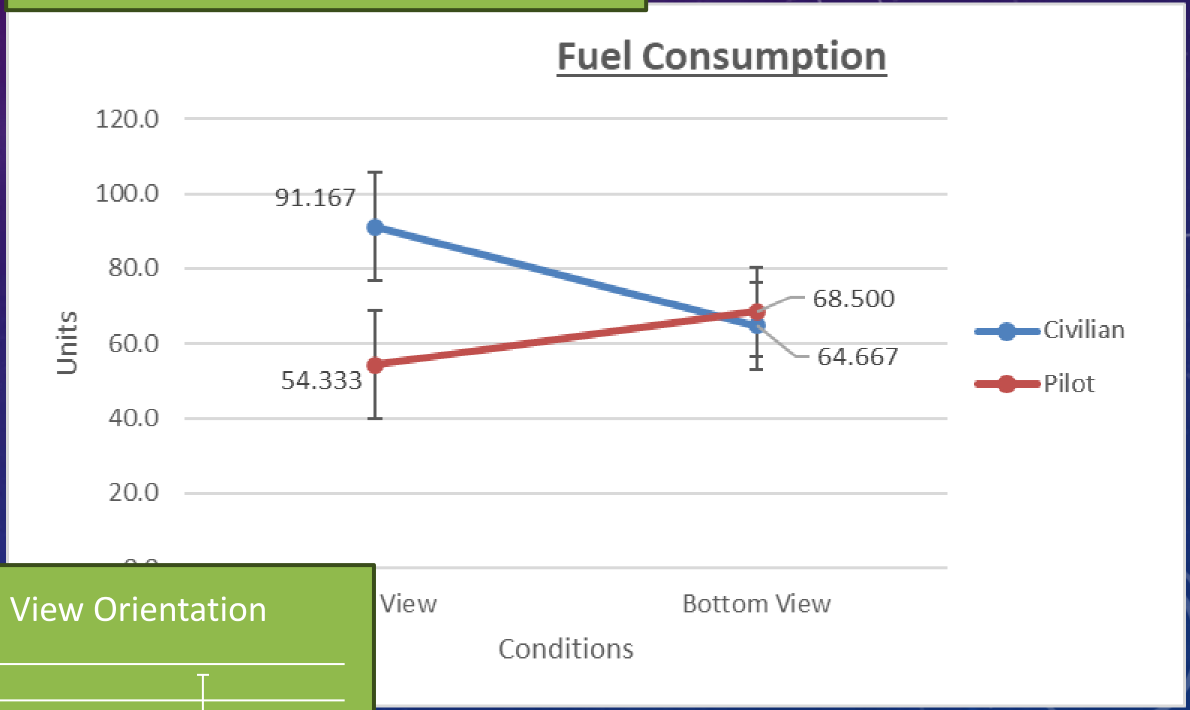
- No significant difference for any other parameter like flight time, fuel, self reported TLX and SUS values

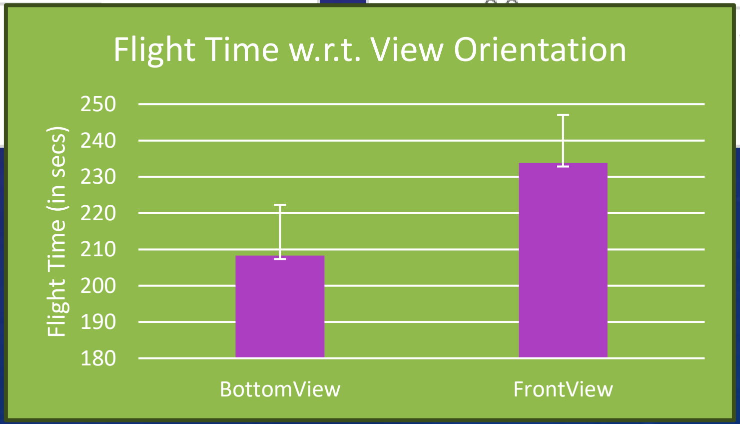


RESULTS – FLIGHT LOG

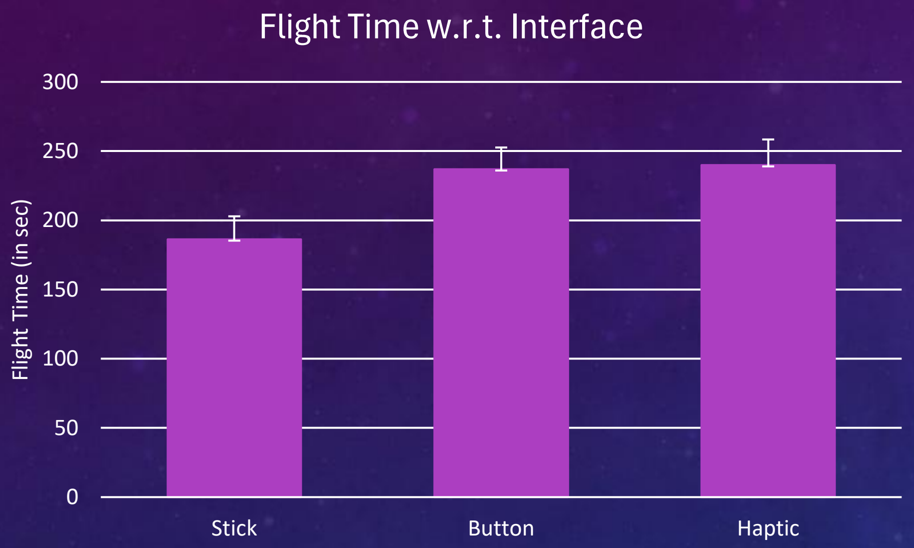


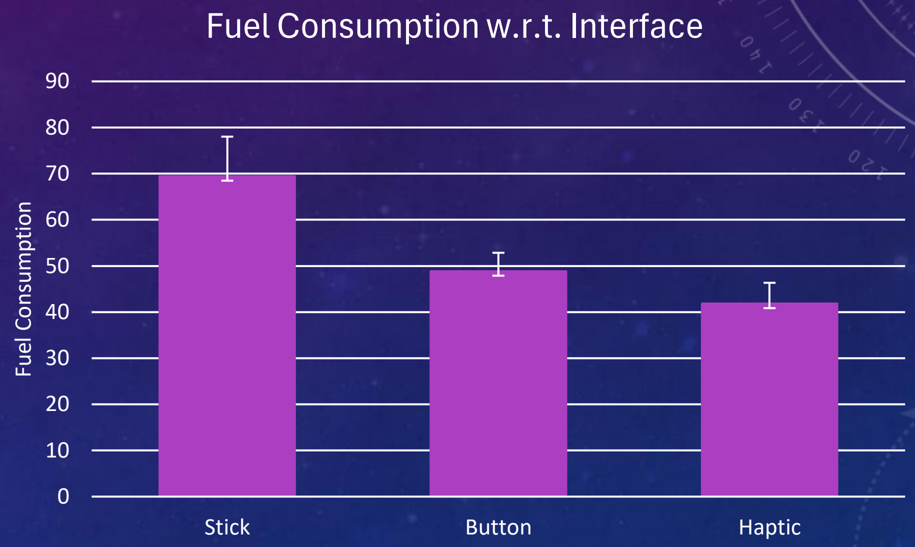






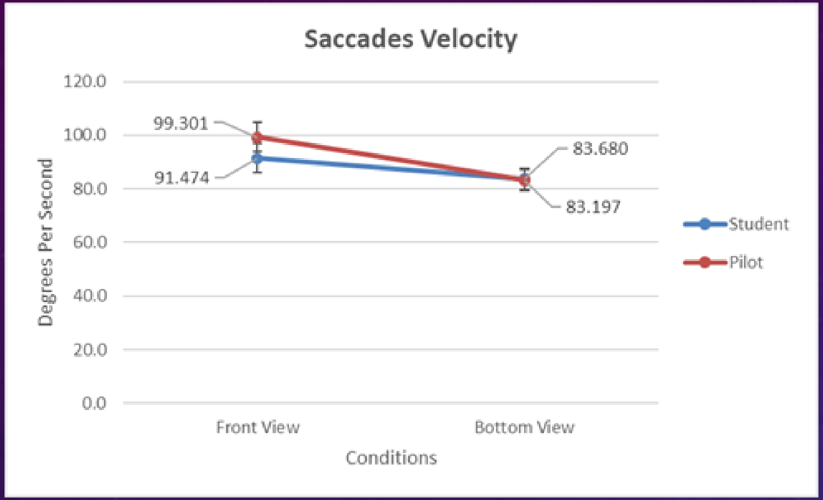
RESULTS - CHOICE OF INTERACTION DEVICE

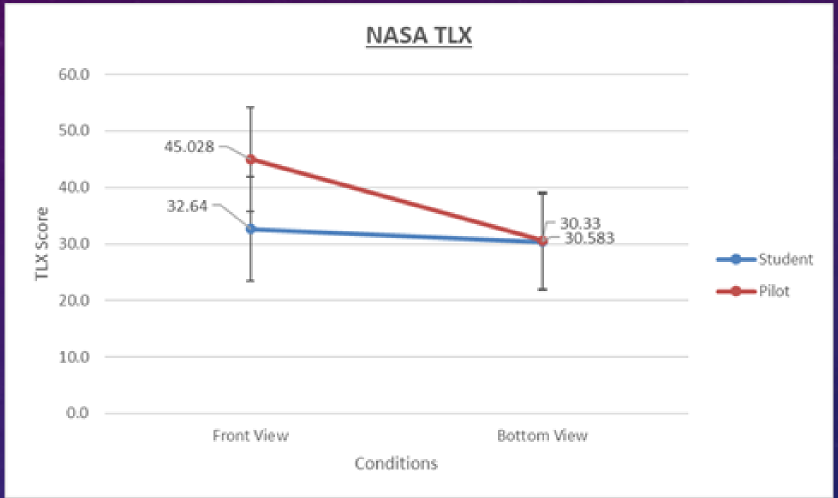


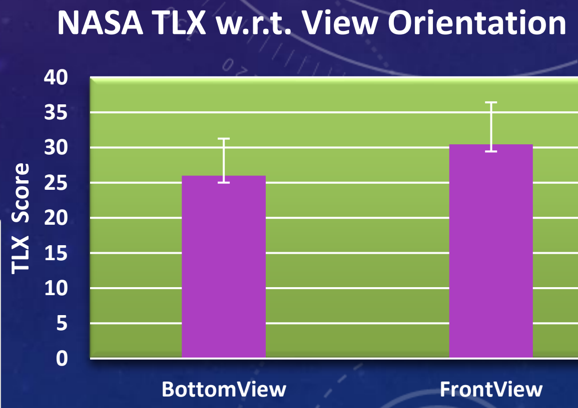


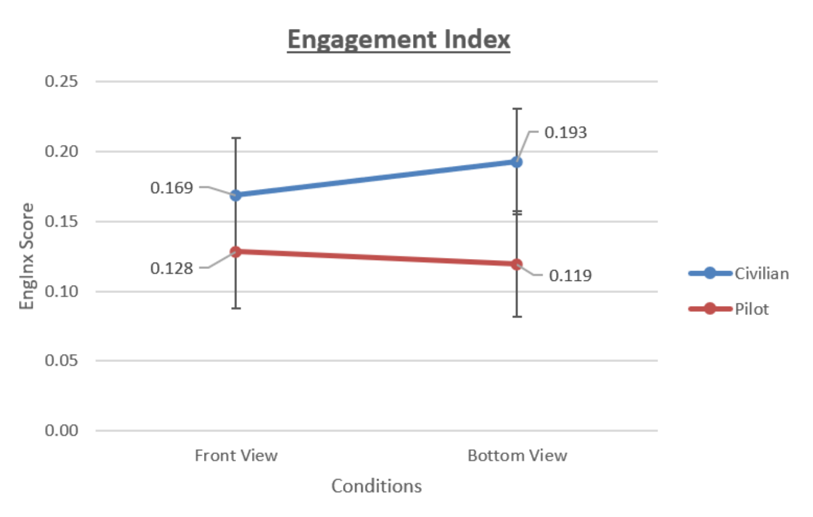
Flight Time: $F(2, 20) = 4.448$, $p=0.025$, partial $\eta^2 = 0.308$, Power=0.696
Fuel Consumption: $F(1.264, 12.640) = 4.741$, $p=0.042$, partial $\eta^2 = 0.322$, Power=0.573

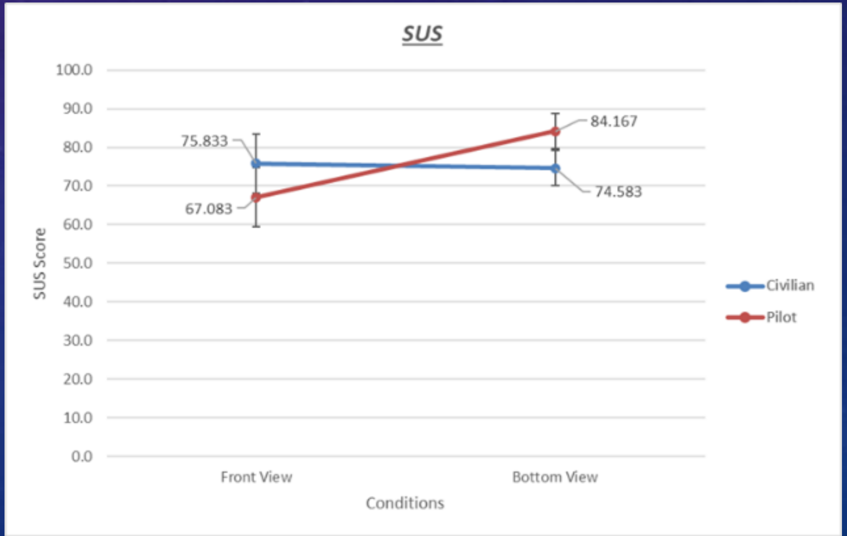
RESULTS – HUMAN FACTORS











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EXPLANATION OF RESULTS – VIEW ORIENTATION

- Front view: Less preferred, takes longer
  - Demands more accuracy and requires careful observation
  - More cognitive load and less preferred by participants

- Bottom view: Pilots use more fuel
  - Small errors in roll and pitch more evident, pilots tend to correct them even while correcting yaw, resulting in higher fuel

EXPLANATION OF RESULTS – INTERACTION DEVICE

- Control stick
  - Force feedback – spring loaded to centre position
  - No need to refer to numeric values on display
  - Most preferred
  - Most fuel consuming – participants more confident to apply minor corrections
- Physical Buttons
  - Does the job well
- Virtual Buttons mimicking touchscreen
  - Least preferred
  - Did not actually mimic touchscreen – lack of depth perception

Conclusion

- Bottom view preferred, less cognitive load.
- While the flight stick was fastest in terms of de-orbiting, physical buttons were most economical in terms of fuel consumption.
- VR simulator and human factor analysis tools for investigation of man-machine interface of spacecrafts.

S No	*Name*	*External Visual Reference*
1	Vostok	Bottom view
2	Mercury	Bottom + Front view
3	Voskhod	Bottom view
4	Gemini	Front view
5	Soyuz	Front + Bottom view
6	Apollo	Front view
7	Space Shuttle	Front view
8	Crew Dragon	Front view
9	Shenzhou	Front + Bottom view
10	CST-100	Front view
11	Orion	Front view
12	Dream Chaser	Front view

PUBLICATION

A Krishnan, H Vishwakarma, M Kharsade, P Biswas, Comparison of View Orientation in Manned Spacecraft Through Virtual Reality Simulation, **IEEE Space 2024**

FUTURE PLANS/ VALUE ADDITION TO HSP

- Docking simulator
- Integration of 6DOF with this project simulator
- Provide inputs on most suitable method – bottom vs front and control stick vs keypad
- Real time visualization of crew view during unmanned missions by integrating with telemetry data
- 6 DOF - Define and refine manual control laws to get HQR 1, similar to NAL CLAW team task
- Atmospheric flight 6 DOF – HQR 1 for atmospheric flight
- Camera/ window specs
- Flight instrumentation determination - most suitable display HMI
- Different types of control schedules– fuel saving, time saving, ease of execution, task accuracy
- Integrate with crew training simulators

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