History of Manual Crew Override

S&MA Flight Safety Office

Safety and Mission Assurance Support Services Contract
Flight Safety Office Support Team

March 7, 2013 – Rev A

Table of Contents

1 Executive Summary 1

2 Introduction and Purpose 4

3 Manual Control Capabilities and Significant Events: U.S. Programs 5

Mercury 5

Gemini 6

X-15 7

Apollo 7

Skylab 10

Apollo Soyuz Test Project 10

Space Shuttle Program 10

Summary of Manual Control for U.S. Programs 12

4 Manual Control Capabilities and Significant Events: Russian Programs 13

Vostok 13

Voskhod 13

Soyuz 14

Progress 18

5 Observations and Recommendations: Manual Control Considerations 20

6 Conclusions 25

Acronyms 26

References 27

Appendix A: Summary Table for Significant Events – U.S. Programs 30

Appendix B: Summary Table for Significant Events – Russian Programs 34

1 Executive Summary

As spacecraft become increasingly more complex and sophisticated, the level of automation increases, while the level of required human interaction decreases. However, these complex systems can fail, and sometimes with catastrophic results. The addition of manual crew control capabilities can provide a useful backup to the automated controls, but it also comes at the expense of budget and schedule, and introduces new risks associated with potential human error. Risk benefit trades must be performed to determine what types of manual crew control capabilities should be incorporated into new spacecraft designs to mitigate risks to flight crew and mission success while staying within programmatic constraints.

In this paper the Safety and Mission Assurance (S&MA) Flight Safety Office (FSO) provides a summary of significant crew manual control events in the history of human spaceflights. This information should aid current and future spacecraft designers in determining which manual control capabilities should be incorporated into their designs. Of the 71 significant crew manual control events identified in this report, 35 events could have resulted in loss of mission, had crew manual control capabilities not been available to support continued mission operations. Nineteen events could have resulted in loss of crew if manual control capabilities were not available. Eighteen events were caused by human errors, inadequate human-system interfaces, procedures, or training, or a combination of these factors, putting the crew and/or mission at risk. An analysis of these events can help inform the decision of whether to include manual crew control in future spacecraft designs. Table 1 provides a summary of manual crew control capabilities for human spaceflight programs and how those capabilities were used.

This review of crew manual control was limited to those safety and mission critical functions of flight control where primary control was automatic with manual override/backup. Other critical spacecraft subsystems where the crew had manual control, such as environmental control, electrical power, communications, etc., were not examined. The report also does not address functions for which the primary control was manual.

Table 1: Summary of Manual Control Capabilities, by Program

Capability		Mercury	Gemini	Apollo	Space Shuttle	Soyuz
		Program				
Pre-launch/Ascent	Abort Initiation	✓	✓	✓	✓	X
	Abort Inhibit	X	✓	✓	✓	X
	Manual Steering	X	X	✓ (2nd & 3rd stage)	✓ (post MET 1:30)	X
	Manual Throttling and Shutdown	X	X	✓ (3rd stage)	✓	X
On Orbit	Abort Initiation	✓	✓ C	✓	✓	✓ C
	Attitude Control	✓ C N	✓ C N	✓ C N	✓ C N	✓ C
	Translation Burns		✓ N	✓ N	✓ N	✓ C
	Rendezvous		✓ C	✓ N	✓ N	✓ C
	Docking/Undocking		✓ N	✓ N	✓ N	✓ C N
Lunar Descent/ Ascent	Abort Inititation			✓		
	Abort Inhibit			✓		
	Attitude Control			✓ C N		
	Translation Burn			✓ C N		
Entry/Landing	Attitude Control	✓ C	✓ C	✓ C	✓ N	✓ C
	Parachute Deployment	✓ C	✓	✓ C	✓ N (drag chute)	X
	Landing Gear Deployment				✓ N	
	Runway Steering				✓ N	

✓ Manual capability was provided
- **N** - used for nominal operations
- **C** - used in a contingency event

X Manual capability was NOT provided

(grey) Capability not applicable to the program

Incorporation of specific manual control capabilities into spacecraft should be based on the following key considerations:

1) Is the function critical for crew safety or primary mission objective?
2) Is the time requirement to perform the function well within the normal human response time and performance envelope, considering the off-nominal environment due to automatic control system failure?
3) Is the crew monitoring of the automatic system sufficient to ensure it can seamlessly enter the control loop?
4) Is sufficient information available to the crew to successfully perform the function?
5) Are there sufficient controls or inhibits in place to preclude inadvertent engagement of manual override capabilities?
6) Is the crew trained/refreshed in the operation on a regular basis?
7) Is the overall function reliability improved for crew safety and mission success with manual control, taking into account human reliability and mission duration impact?
8) Does the overall risk/benefit trade support implementation of manual override capabilities when considering technical, cost, and schedule impacts?

Past experience demonstrates a need for a manual backup to the automatic control for crew safety and the capability to successfully complete high-value, primary mission objectives. Achieving these goals will require an ideal mix of automatic control and manual crew override with the inclusion of human factors in the design and implementation.

2 Introduction and Purpose

With increasing complexity comes an increasing reliance on automation and a decrease in human control. However, complex automated systems can fail. To mitigate the risk of an automatic system failure causing a catastrophic result, NASA's human rating requirements contained in NPR 8705.2B, *Human-Rating Requirements for Space Systems* require manual crew control or override capability for critical automated functions. While these manual crew control capabilities provide a useful backup to the automated controls, they also come at the expense of budget and schedule, and introduce new risks associated with potential human error. Risk benefit trades must be performed to determine what types of manual crew control capabilities should be incorporated into new spacecraft designs to mitigate risks to flight crew and mission success while staying within programmatic constraints.

Throughout the history of human spaceflight, there are examples of crew manual control allowing the mission or the crew to be saved following an in-flight anomaly. In this paper the S&MA FSO provides a summary of significant crew manual control events during crewed spaceflights. This information should aid current and future spacecraft designers in determining which manual control capabilities should be incorporated into their designs.

Of the 71 significant crew manual control events identified in this report, 35 events could have resulted in loss of mission, had crew manual control capabilities not been available to support continued mission operations. Nineteen events could have resulted in loss of crew if manual control capabilities were not available. Eighteen events were caused by human errors, inadequate human-system interfaces, procedures, or training, or a combination of these factors, putting the crew and/or mission at risk. These events can help inform the decision of whether to include manual crew control in future spacecraft designs.

This paper focuses on historical United States (U.S.) and Russian human spaceflights for which manual backup control saved the mission, and in some cases the crew as well. The review of crew manual control was limited to those safety and mission critical functions of flight control where primary control was automatic with manual override/backup. The review did not include other critical spacecraft subsystems where the crew had manual control, such as environmental control, electrical power, communications, etc. The report also does not address functions for which the primary control was manual.

Data was sourced from familiarization manuals, systems handbooks, operations manuals, mission reports, historical books on human spaceflight, books authored by astronauts and cosmonauts, NASA International Space Station (ISS) databases, and various web sites. A complete list of references is included at the end of the report.

Early in the development of U.S. spacecraft a high level of crew involvement was used along with automation. The Russian approach was just the opposite, with automation and ground control as the primary mode with little crew involvement. New programs will need to perform a reliability analysis to determine the best application for manual backup controls on new spacecraft.

3 Manual Control Capabilities and Significant Events: U.S. Programs

Early in the development of U.S. spacecraft a high level of crew involvement was used along with the automation of time critical functions like emergency escape and flight control. As mission requirements and technology grew, the number of automated functions increased. However, manual backup to automation was retained for functions where loss of automation could be catastrophic. This summary focuses on manual override or backup controls for critical functions, such as abort and flight control, the failure of which could result in loss of mission (LOM) or loss of crew (LOC). It does not discuss systems which are usually not as time-critical in their impact on LOM or LOC, such as environmental control, electrical power, communications, instrumentation, etc.

Mercury

The majority of the Mercury spacecraft functions were manually controlled. However, some critical functions such as emergency escape and flight control were controlled automatically with manual crew backup/override. There was no manual control for Mercury launch vehicles. Here is a list of automated functions with manual backup: (SEDR 104-18, Project Mercury Familiarization Manual 1962)

1) Escape System – The escape system primarily consisted of a tower assembly designed to provide a safe means of abort between pre-launch and staging. By utilizing the posigrade rocket system, escapes could still be initiated after booster staging and throughout sustainer operation until orbit. Even if the spacecraft did not attain orbital velocity, the quickest method for re-entry was by emergency firing of retro rockets. After liftoff, there were three methods by which an abort could be initiated: (a) ground command receiver abort signal, (b) astronaut abort handle, and (c) the Booster Catastrophic Failure Detection system.

2) Retrograde Rocket System – The retrograde rocket system consisted primarily of the three retro-rockets, their pyrogen igniters, and the associated wiring. The retro-rockets were housed in the jettisonable retrograde package along with the posigrade rockets. The method of initiating normal re-entry sequence was by closing the Retrograde Firing Signal switch within the Satellite Clock. This illuminated the Green Retro Sequence Indicator light. The switch could be activated by the run-out of time pre-set into the clock prior to launch for a calculated re-entry time, from booster liftoff. The time could also be pre-set by the astronaut or by ground command when necessary. The astronaut could bypass the satellite clock to start the sequence by pressing the Retro Sequence button.

3) Retro-Rocket Emergency Override – If the Retro Attitude Light illuminated red, the astronaut checked the spacecraft attitude for proper retrofire position. If the spacecraft was in the correct attitude, then the astronaut could manually position the RETRO ATT switch to the bypass position, and also push the FIRE RETRO button. If the spacecraft were not in the correct attitude, the astronaut could use the manual fly-by-wire system to correctly position the spacecraft.

4) Fly-By-Wire – In the fly-by-wire position, the Automatic Stabilization Control System (ASCS) was disabled and 24 volts of direct current were connected to the fly-by-wire limit switches on the astronaut's control stick, which applied power to the Reaction Control System (RCS) valve solenoids.

5) Manual System – The manual system consisted of six thrust chambers of the same configuration as those in the automatic system with proportional thrust output added. The fuel flow in the manual system could be controlled only by the mechanical linkages from the control handle to the RCS proportional control valves. A two-position manual shutoff valve was provided to place the manual system either on or off.

During the Mercury Program's six Mercury Atlas (MA) crewed flights, two suborbital and four orbital, the astronaut on MA-6 had to take over manual fly-by-wire control when the yaw reaction jet caused an attitude control problem. He used fly-by-wire control for on-orbit and entry capsule control. He later manually changed entry procedures following instructions from Mercury Control to keep the retropack attached during entry. (Carpenter, et al. 1962)

On MA-7 the automatic control system did not maneuver the capsule into the correct retro-rocket attitude. The astronaut switched over to fly-by-wire control, but he failed to shut off the manual system, draining hydrogen peroxide fuel from both systems. This crew error caused excessive RCS fuel usage, and depletion occurred between 70,000 and 80,000 feet. With loss of RCS the capsule started swinging through a large 270 degree arc. He manually deployed the drogue chute to stabilize the capsule (26,000 feet verses 21,000 feet). Another crew error in yaw at retro-rocket firing, which prevented the capsule from slowing down as much as it should have, resulted in an overshoot of the planned landing site. (Encyclopedia Astronautica: Mercury MA-7) (Carpenter, et al. 1962)

On MA-9, when the automatic control system failed due to a short in the electrical system, the astronaut had to use manual control to deorbit and control the spacecraft. This demonstrates the need for a manual backup capability for critical spacecraft functions that could cause loss of crew. (Swenson, Grimwood and Alexander 1989) (Encyclopedia Astronautica: Mercury MA-9)

Gemini

The majority of the Gemini spacecraft functions were manually controlled. However, some critical functions such as abort and flight control were controlled automatically with manual crew backup/override. Those functions were: (SEDR 300 Volume 1, Project Gemini Familization Manual)

1) Malfunction Detection System (MDS) and Egress Systems and Devices – The egress systems and devices provided the astronauts with a rapid and positive method of escaping the spacecraft, should an emergency arise. Initiation of the system was manual only and was used only below an altitude of 70,000 feet. Emergencies were detected using the Gemini launch vehicle (Titan II) MDS, which was triggered by losing stage 1 hydraulic pressure or exceeding stage 1 or 2 roll, pitch, yaw rate, or tank pressure limits. If the MDS detected an out-of-limit condition, it sent a signal to illuminate the spacecraft cabin abort light. Alternatively, ground command could illuminate the abort light. To egress, either the commander or pilot would pull the ejection control handle ("D" ring) located between his knees. The Hatch Actuator Initiation System was used to initiate the firing mechanisms of both hatch actuators. The Hatch Actuator Assembly unlocked, opened, and mechanically restrained the egress hatch in the open position. The assembly also furnished sufficient pressure to initiate the firing mechanism of the seat ejector-rocket catapult, used to eject the crew member and seat from the spacecraft. The Harness Release Actuator Assembly, which was installed on the seat structure, actuated the restraint harness release mechanism and initiated the firing mechanism of the thruster assembly. The firing mechanism was initiated by lanyard pull when the seat rose on the ejection rails. The Ballute Deploy and Release System primarily consisted of the firing assembly, deploy cutter and hose, and release guillotine and hose. The system was initiated by the lanyard pull as seat/man separation was effected. The drogue mortar ejected a weighted slug with sufficient velocity to forcibly deploy the pilot chute of the personal parachute. The drogue mortar was initiated by the pull of the main lanyard, as the astronaut was separated from the seat. The drogue mortar could be initiated manually by pulling the manual lanyard handle.

2) Orbital Attitude and Maneuver System (OAMS) – The OAMS was a bipropellant rocket engine propulsion system consisting of two 95-pound translation thrusters, eight 23-pound attitude control thrusters, two 79-pound, and four 95-pound thrusters with associated plumbing, tanks, and electronic modules, located in the Gemini adapter equipment section. Attitude control was either manual via attitude hand controller or automatic via the attitude control maneuver electronics (ACME). The crew could select primary or secondary control to use the automatic system or override the automatic ACME. Velocity control was provided along three translation axes, and there were no provisions for automated velocity control.

3) Re-entry Control System – The Re-entry Control System was a bipropellant rocket engine propulsion system consisting of eight 23-pound thrusters located in the RCS section between the re-entry module cabin and the rendezvous and recovery section. The crew could select between two completely independent Re-entry Control System rings, A or B, to direct to bypass or override the automatic ACME.

4) Retrograde Rocket System (RRS) – The RRS consisted of four solid propellant rocket motors mounted in the retrograde section of the adapter. Each had 2500 pounds of thrust that fired sequentially and automatically when triggered by an electrical signal from an onboard electronic timer. There was also a manual backup initiation capability. In the event of an abort before orbital altitude and velocities were achieved, the retrograde rockets could be salvo fired by the flight crew to aid in separating the spacecraft from the launch vehicle.

5) Ascent Titan Launch Vehicle Guidance – The Titan was the primary system for ascent guidance, but the crew could manually switch to the Gemini computer for backup ascent guidance for both the first and second stages.

During the Gemini Program's 10 crewed flights, there were four instances of astronauts using manual backup when an automatic system failed. The astronauts on Gemini 4 had to perform a rolling manual entry when the on-board computer failed. Due to a computer programming error the astronauts on Gemini 5 had to take manual control to minimize the resulting landing point error. The astronauts on Gemini 8 had to manually select the entry RCS system to regain spacecraft control, saving the spacecraft and crew.

On Gemini 12 the backup manual capability was used for rendezvous when the automatic rendezvous mode radar failed. Due to problems with the Orbital Attitude and Maneuver System attitude control thrusters, the crew had to select manual control and use translation thrusters along with attitude thrusters to restore the spacecraft to a stable attitude, while on orbit (Gemini 12 Mission Report January 1967). This allowed for successful completion of the primary objective to dock with the Agena target vehicle. (Grimwood and Hacker 1977)

X-15

One of the NASA research flights with the X-15 had an electrical disturbance that deactivated the automatic reaction control system. After the pilot took over manual control, he misinterpreted the attitude indicator as sideslip rather than roll angle and made a yaw input to the right that increased the heading deviation. The adaptive control system became saturated and prevented the pilot from regaining control, causing loss of research aircraft, mission, and pilot. Software control limits in the adaptive control system contributed to the inability of the pilot to regain control. (Jenkins 2000)

Apollo

The majority of the Apollo spacecraft functions were manually controlled. However, some critical functions were controlled automatically with manual crew backup/override. For critical human spacecraft functions (where failure causes loss of spacecraft and crew) the Apollo spacecraft had manual control added to back up the dual automatic control. The NASA Apollo Program design requirement was to have no single-point failures (fail safe) that would cause loss of crew and two levels of redundancy, for example Main Direct Current (DC) Bus A and Main DC Bus B. However, when new technology unproven by previous flight history was to be used, three levels of redundancy (fail op/fail safe) were used. This is the reason the Apollo Crew/Service Module (SM) had three fuel cells even though it only had two main buses and three solid–state alternating current (AC) inverters with two AC Buses (AC 1 and AC 2). This extra level of redundancy allowed for the Apollo 10 mission to continue when a fuel cell failed in lunar orbit.

Some of the functions which had a manual backup control were:

1) Launch Escape System (LES) Abort – The Saturn launch vehicle Emergency Detection System (EDS) provided the ascent abort information from the launch vehicle to the command module (CM). The EDS system was triple redundant, voted two out of three, to preclude single point hardware or sensing failures causing an inadvertent abort (single-failure tolerant). Ascent abort was automatically initiated if the launch vehicle exceeded predefined abort limits. All functions to recover the spacecraft and crew were also automated. The commander could manually initiate an ascent LES abort by twisting the translation hand controller counter-clockwise. Crew abort action was based on two separate but related abort cues. These cues were derived from the EDS displays, ground information, physiological cues, or any combination of two valid cues. Ascent abort was never required during the Apollo launches.

2) Earth Landing System (ELS) – When the automatic Earth Landing System was enabled there was a System A and B, either of which could jettison the apex cover, deploy the drogue parachutes, and deploy the main parachutes based on barometric altitude. The crew, by activating push button switches, could manually jettison the CM apex cover, deploy the drogue parachutes, and deploy the main parachutes. During the Apollo Soyuz Test Project (ASTP) CM entry and landing the crew members failed to enable the automatic ELS (ELS logic switch to on) and, recognizing they were below the deployment altitude, they had to manually perform the ELS functions. This manual capability saved the ASTP crew.

3) Reaction Control System – The Command and Service Module (CSM) had two Stabilization and Control Systems for automatic RCS control (A and B). The crew could select RCS Controller Power Direct to either Main Bus A or Main Bus B, and the crew could control the CSM or CM attitude with the rotational hand controller. During the Skylab 4 entry preparation the crew mistakenly unpowered the CSM Stabilization Control System (SCS), which automatically provided RCS attitude control. When the CM separated from the SM, the crew members saw the CM was apex forward, and they could not maneuver to the correct entry attitude (CM aft heatshield forward). The crew switched the RCS Direct to On, regained CM RCS control, and put the spacecraft in the proper entry attitude. This manual capability saved the Skylab 4 crew.

4) Docking System – When two of the three capture latches closed (soft capture), the CSM docking probe was automatically enabled to allow the crew to retract the probe, causing the docking structural latches to trip/close (hard dock) when contact was made with the Lunar Module (LM) or Skylab docking interface. During the Skylab 2 mission, when the crew was unable to obtain soft capture after multiple attempts, a manual backup procedure was used to bypass the capture latch circuits and apply power to retract the probe, while the commander manually thrust the CSM forward, causing the Skylab docking interface to contact and trip the structural latches, achieving hard dock. This saved Skylab as this crew had to install a protective sun shield.

5) Service Propulsion System (SPS) – The CSM SPS engine was the main engine used for course correction of the CSM docked to the LM, going to (translunar coast) and from the moon (transearth coast), and the engine used to put the CSM/LM into Lunar Orbit Insertion (LOI), and for the CSM transearth injection burn. The crew had the capability to perform a manual SPS engine burn by switching the SPS Thrust from Normal (auto) to Direct On. During the Apollo missions the automatic system did not fail, and the crew was not required to perform a manual SPS engine burn.

6) Lunar Module Primary Guidance and Navigation System (PGNS) – During landing, the primary guidance system automatically controlled and landed the LM at a targeted landing area. The crew had the capability to switch to semi-automatic control (automatic attitude control and manual translation) and manually control the landing. This was done on Apollo 11, 12, 14, 15, 16, and 17 either to avoid hazardous terrain in the landing areas or to get closer to the planned landing site.

   During rendezvous, the primary guidance system automatically controlled the LM's rendezvous with the CSM in lunar orbit. During LM rendezvous with the CSM in lunar orbit on Apollo 10 the commander, investigating a possible electrical problem, inadvertently hit the Stabilization/Control, Mode Control, AGS (Abort Guidance System) switch from Attitude Hold to Auto, which caused the LM guidance system to look for the CSM immediately, causing the LM to flip end-over-end. The commander quickly grabbed the hand controller, switched to manual, and jettisoned the LM descent stage, regaining control of the LM and successfully completing rendezvous and docking with the CSM. This manual capability may have saved the Apollo 10 LM crew.

7) Lunar Module Descent and Ascent Engines – The PGNS controlled the descent and ascent engine burns and AGS could also control the engines. The crew had the capability to manually start and stop the descent and ascent engine burns by pushing the start or stop button. The Engine Trust Control, Engine Arm switch would have to be positioned from "off" to the descent or ascent position, depending on which engine was to be fired. During the Apollo missions the crew did not have to perform those burns manually. As discussed above, descent engine manual control was only done during the lunar landing phase of the mission with manual shutdown of the engine.

8) Saturn V Launch Vehicle Guidance – During the S-II (second stage) and S-IVB (third stage) burn phases the crew's rotational hand controller was used to generate the attitude error signals, if launch primary guidance failed.

During the Apollo Program's 11 crewed missions, the backup manual control system was used in the following ways: The crew on the Apollo 10 had to manually regain control of the LM to rendezvous and dock with the CSM due to a crew switch misconfiguration during rendezvous (Stafford 2002) (Encyclopedia Astronautica: Apollo 10). During the Apollo 11, 12, 14, 16, and 17 lunar landings the commander took over semi-automatic control manually because of hazardous terrain at the computer's targeted landing site (Stafford 2002) (NASA MSC-00171, Apollo 11 Mission Report November 1969) (NASA MSC-04112, Apollo 14 Mission Report May 1971) (NASA MSC-07230, Apollo 16 Mission Report August 1972) (NASA JSC-07904, Apollo 17 Mission Report March 1973).

During the Apollo 15 lunar landing the commander took over semi-automatic control manually to land in the pre-selected landing target, preventing the loss of this mission objective. (NASA MSC-05161, Apollo 15 Mission Report December 1971). On Apollo 12 during ascent, when lightning caused a disconnect of fuel cell power and AC power, and the loss of the on-board computer, the crew was able to manually regain power and flight control preventing loss of the mission. (NASA MSC-01540, Analysis of Apollo 12 Lightning Incident February

1970). On Apollo 13 the SM oxygen tank explosion resulted in the loss of CSM oxygen and electrical power. A complete power-down of the CSM and major power-down of the Lunar Module resulted in manual crew control of the spacecraft (NASA MSC-02682, Apollo 13 Mission Report September 1970).

Skylab

During the Skylab Program on two of the three crewed missions the crew had to use a manual procedure. The Skylab 2 crew was unable after many attempts to obtain CSM docking probe capture, which automatically retracts the docking probe and trips the docking latches for a hard dock. The crew had to use a manual procedure to bypass the capture interlock and manually retract the probe, then thrust the spacecraft forward to trip the docking latches, which completed the docking. During de-orbit the Skylab 4 crew pulled the stabilization and control system pitch and yaw circuit breakers instead of the service propulsion system pitch and yaw circuit breakers, which caused a loss of automatic CM RCS control when the SM was jettisoned. They had to go to manual CM RCS control to get into the proper attitude for entry. Having manual direct RCS control prevented the possible loss of spacecraft and crew. (Compton and Benson 1983) (Hitt, Garriott and Kerwin 2008) (JSC-08053, Skylab 1/2 Technical Crew Debriefing June 30, 1973) (JSC-08809, Skylab 1/4 Technical Crew Debrief February 22, 1974)

Apollo Soyuz Test Project

On the ASTP the second docking of the Apollo CSM to the Soyuz spacecraft was a very hard docking due to crew error. At about 100 meters, with docking target washout and against the earth background, the pilot pressed on with the docking anyway. Then after contact, the pilot inadvertently fired roll thrusters for three seconds, causing the Soyuz to sway. (Note: During the Shuttle/Mir Program the Russians were concerned that the U.S. vehicle had no automatic docking capability and relied on crew control only, due to what happened during ASTP.)

During entry the ASTP crew failed to enable the automatic ELS, and when the crew members recognized they were below the normal parachute deployment altitude, they had to manually initiate the ELS functions. The below-normal altitude resulted in the cabin pressure relief valve being open, and during the propellant dump sequence toxic nitrogen tetroxide (N_2O_4) was drawn into the crew cabin and resulted in the crew having to be hospitalized. (JSC-09823, ASTP Technical Crew Debriefing August 8, 1975) (Stafford 2002) (JSC-10638, Apollo Soyuz Mission Anomaly Report No. 1: "Toxic Gas Entered Cabin During Earth Landing Sequence" December 1975) (Ezell and Ezell 1978)

Space Shuttle Program

For the Space Shuttle Orbiter, advancements in avionics and increases in vehicle design and mission complexity resulted in the use of more automation of flight control functions. However, crew manual capability was implemented for landing, docking, systems management, reconfiguration of the flight control system, subsystem reconfiguration, Remote Manipulator System (RMS), and payload operations. The RMS had both automatic and crew manual modes of operation. In addition to these manual control capabilities, the shuttle had the following contingency manual override capabilities: (USA007587, Shuttle Crew Operations Manual October 15, 2004)

1) Manual control of the Space Shuttle Main Engine (SSME) throttles was available in response to certain SSME anomalies during ascent.

2) Manual control stick steering was available in the event of failures in the auto-guidance flight control system. For ascent, this manual capability was only available after 90 seconds mission elapsed time,

post-max q-bar (flight rule A2-59). In the manual control stick steering mode, flight crew commands input via commander and pilot hand controllers, speed brake and rudder pedals, still passed through and were issued by the general purpose computers (fly-by-wire). During all phases of flight except ascent, the flight control system automatically changes from automatic mode to manual control stick steering when the commander or pilot's rotational hand controller deflection exceeds the detent in any axis. During ascent, control stick steering pushbuttons must be depressed to change the flight control system from auto to manual control.

3) Contingency manual SSME shutdown capability was available in the event of an SSME anomaly and failure of the automatic systems to shut down and safe the system. The crew could also enable and disable automatic SSME shutdown limits.

4) The crew could manually initiate aborts during ascent in the event the automatic system failed to detect and initiate an abort, using either the abort mode rotary switch and abort pushbutton or a command entered into a Primary Avionics Software System keyboard. The crew also had the capability to manually command external tank separation using an external tank separation switch and pushbutton.

5) Manual attitude and translation control were available during on-orbit operations. Attitude and translational maneuvers could be performed by the crew using hand controllers located at the commander's station and aft flight deck station, which sent commands to the Reaction Control System thrusters.

Due to the redundancy of most onboard systems, no immediate action was required for most single and many dual failures (fail ops, fail safe avionics design). However, if multiple failures occurred, there might be very little time to switch to alternative systems or take the necessary steps to prevent loss of control. In multiple failure cases, the crew would have to keep in mind the interaction of different systems and prioritize their responses.

During the Space Shuttle Program's 135 missions, there was one instance during the STS-9 landing in which crew error caused a loss of automatic control, and there was one notable instance during STS-32 in which contingency manual crew control of the orbiter vehicle was used to regain control of the vehicle. During the STS-9 landing, the General Purpose Computer-2 (GPC-2) failed and resulted in the pilot performing a reconfiguration based on a normal GPC configuration, causing the loss of the flight control system during rollout, due to the reconfiguration from the off-nominal GPC configuration. The pilot had no visual display of what the current GPC configuration was and would have had to remember what the current configuration was after his last restring of the avionics.

On the STS-32 mission an erroneous state vector that the Mission Control Center (MCC) up-linked to the flight control system caused immediate attitude flight control problems that required MCC to awaken the crew, and the crew to manually regain control of the orbiter. (STS-32: Uplink Error Caused Vehicle Attitude Change April 25, 2005) (Peters May 12, 2005) (NASA/TM-2011-216142, Space Shuttle Missions Summary September 2011)

There were also several instances in which crew manual control put the crew at risk either due to human error, inadequate human-system interfaces, procedures, or training, or a combination of these factors. STS-3, STS-37, and STS-90 are examples of this. On STS-3 the final transition from autopilot to crew manual control was delayed to test the orbiter automatic landing capabilities. This late transition did not allow the commander sufficient time to become familiar with the vehicle handling characteristics prior to landing, which involves relatively complex flare and derotation maneuvers. Additionally, the landing occurred at the alternate landing site in New Mexico which is at a higher altitude than the nominal landing site (thus having lower atmospheric pressure and drag). These factors resulted in a hard, fast landing and pilot induced oscillation during derotation.

(O'Connor May 1, 2006) (Lessons Learned 0194 1994) During approach on STS-37 the commander misinterpreted the indication of low energy around the hack as high energy, and the high winds at lower altitude resulted in a low energy landing that was 623 feet short of the runway threshold. (Peters May 12, 2005) On STS-90 manual control during landing resulted in a hard, fast landing due to human factors and a rogue wind gust. (Peters May 12, 2005) (NSTS 37420 STS-90, Space Shuttle Mission Report June 1998)

There were also a number of cases in which the shuttle commander or pilot inadvertently disengaged the orbiter auto-guidance flight control system, or Digital Auto Pilot (DAP), by bumping into one of the hand controllers during entry preparation. However, in all these cases the inadvertent disengagement of DAP was detected by either the flight or ground controllers and quickly resolved without incident.

For many orbiter functions the primary control was manual. All landing and dockings to Mir or ISS were performed manually. Many major functions were performed manually, such as landings (including landing gear and drag chute deployment), on-orbit payload operations, and system reconfigurations such as environmental control and electrical power.

Summary of Manual Control for U.S. Programs

Table 2 provides a summary of historical U.S. human spaceflight incidents with respect to contingency crew manual control events and potential worst case impacts. Roughly 10% of the U.S. crewed missions required some form of contingency manual crew control capability to either protect the crew or prevent loss of primary mission objectives. Improvements in spacecraft design, development, test, and verification have resulted in fewer incidents where contingency crew control was necessary to protect the flight crew, as evidenced by the smaller number of incidents during the Space Shuttle Program. Though the frequency of these contingency events appears to be declining, given the potentially catastrophic consequences involved, manual crew back-up capabilities should continue to be a key design aspect of future crewed spacecraft. When implementing manual control capabilities, special attention should be paid to human factors in order to minimize the potential for human error, which could easily negate the benefits of manual control features.

Table 2. Summary of U.S. Missions for Which Manual Control was Necessary to Prevent LOC or LOM

NASA Programs	**Number of Missions**	**Number (and Percentage) of Missions Requiring Crew Control to Prevent LOC or LOM**		
		LOC	**LOM**	**Total**
Mercury	6	3	0	3 (50%)
Gemini	10	2	1	3 (30%)
Apollo, Skylab, and ASTP (Command/Service Module)	15	4	7	11 (73%)
Space Shuttle	135	1	0	1 (1%)
Total Capsule Design	31	9	8	17 (55%)
Total with Space Shuttle	166	10	8	18 (11%)

4 Manual Control Capabilities and Significant Events: Russian Programs

The Russian Vostok spacecraft, which was used for the first human spaceflights, was designed to be fully automated. The first two missions were uncrewed flights prior to Yuri Gagarin's Vostok 1 mission. The Russian crewed Vostok and Voskhod spacecraft relied primarily on automation and ground command capability, with very limited crew manual control capability. The Soyuz spacecraft had increased crew involvement and added capabilities for manual docking and on-orbit control. However, the amount of Soyuz crew control is still very limited compared to the U.S. spacecraft.

Vostok

The Vostok carried a single crew member, and all of the critical functions were automatically controlled. The crew member manually ejected prior to landing. The manual orientation control system for on orbit and re-entry attitude was provided as a redundant backup to automatic. The following is a list of manual functions for Vostok: (Encyclopedia Astronautica: Vostok)

1) Escape System – The Escape System was an ejection seat that allowed the pilot to eject at 8 to 10 kilometers of altitude after re-entry and land by parachute. Parachute ejection used both inertial and barometric sensors. For an emergency ejection during ascent to orbit, only the spacecraft designer (Korolev) or cosmonaut commander (Kamanin) was allowed to manually command an ejection in the first 40 seconds of flight. After that the process was automatic.

2) Retrofire Rocket Engine System – The nitrous oxide/amines rocket engine was not restartable and was used only at the end of the mission for the re-entry braking maneuver. The FSO found no mention of manual backup for on-and-off control of the engine. However, this type of manual backup was mentioned as being used on the Voskhod 2 mission. Since Voskhod was basically a Vostok spacecraft, the crew on Vostok may have had this capability also.

3) Orientation Control System – The orientation system consisted of two redundant systems: an automatic/solar orientation system and a manual/visual orientation system using a floor-mounted periscope. Either system could operate two redundant cold nitrogen gas thruster systems, each with 10 kilograms of gas. The cosmonaut cold also take manual control of the spacecraft and manually orient for re-entry. Control for entry was passive. The spherical design had no maneuvering engines, and with heavy weight at one end it automatically oriented to the re-entry attitude, which was always a ballistic re-entry.

During Vostok 1, Yuri Gagarin's controls were locked to prevent him from taking control of the spacecraft. The combination to unlock the controls was available in a sealed envelope in case it became necessary to take control in an emergency. During Vostok 2 a crew member used manual orientation on orbit. During the joint Vostok 3 and 4 mission, a crew member used manual orientation on orbit. During Vostok 6, Valentina Tereshkova (the first woman in space) noticed immediately during orbit insertion that her capsule was oriented 90 degrees from the intended direction. The automatic orientation system was incorrectly configured. She advised the ground control team and signals were sent on the second day to correct the problem. For return to earth she used the manual orientation for proper entry attitude. Manual backup control saved the crew on Vostok 6. A total of six Vostok missions were flown.

Voskhod

The Voskhod was basically a Vostok spacecraft that had a backup, solid fuel retrorocket added to the top of the descent module. The ejection seat was removed, and two or three crew couches were added. The Elburs soft landing system replaced the ejection seat and allowed the crew to stay in the capsule during landing. This system consisted of probes that dangled from the parachute lines. Contact with the earth triggered a solid rocket engine in the parachute, which resulted in a zero velocity landing. Like Vostok, all of the critical functions were automatically controlled. A manual orientation control system for on-orbit and re-entry attitude and manual on/off command to the retrofire engine were provided as redundant backup to the automatic systems. In the case of Voskhod 2, an inflatable exterior airlock was also added to the descent module opposite the entry hatch. Only two missions were flown, as the vehicle was superseded by the much more capable Soyuz spacecraft. This following is a list of manual functions for Voskhod: (Encyclopedia Astronautica: Voskhod 1) (Scott and Leonov 2004)

1) Escape System – With the lack of an ejection seat and crew parachute there was no provision for crew escape in the event of a launch or landing emergency. Up to T+27 seconds, there was no possibility of saving the crew in the event of a booster failure. From T+27 seconds to T+44seconds, escape would have been difficult, but was possible. From T+44 seconds to T+501 seconds abort should have been possible, with the capsule landing on Soviet territory.

2) Retrofire Rocket Engine System – The nitrous oxide/amines rocket engine was not restartable and was used only at the end of the mission for the re-entry braking maneuver. The added solid fuel rocket was a backup. The crew had the capability to start and stop the nitrous oxide/amines rocket engine.

3) Orientation Control System – The orientation system consisted of two redundant systems: an automatic/solar orientation system and a manual/visual orientation system using a floor-mounted periscope. Either system could operate two redundant cold nitrogen gas thruster systems, each with 10 kilograms of gas. The cosmonaut could also take manual control of the spacecraft and manually orient for re-entry. Control for entry was passive. The spherical design had no maneuvering engines, and with heavy weight at one end it automatically oriented to the re-entry attitude, which was always a ballistic re-entry.

The FSO found only one Voskhod mission where the loss of automatic spacecraft control or events necessitated the use of manual control. The Voskhod 2 mission was flown by Commander Pavel (Pasha) Belyayev and Pilot Alexei Leonov. Leonov later reported, "Just five minutes before our retro-engine was due to start, I checked our instruments and realized our automatic guidance system for re-entry was not functioning correctly. The rolling had started again. We would have to switch off the automatic landing program. This meant we would have to orient the spacecraft before re-entry manually, and would also have to select our landing point manually and decide on the exact timing and duration of the retro-rocket firing . . . As soon as Pasha turned on the engines we heard them roar and felt a strong jerk as they slowed our craft." (Scott and Leonov 2004) (Leonov 2005) They safely landed in deepest Siberia. In this case, the manual backup control system saved the crew.

Soyuz

Manual Control Capability

The Russians provided a manual backup to the primary automatic capability for on-orbit orientation and attitude control, deorbit burn, and docking the Soyuz spacecraft to a space station (Salyut, Mir, and ISS). On Soyuz three control strings were used, with two out of three voting for the commands, as there was also a requirement of no single-point failures that would cause loss of crew. This manual capability was used several times for Soyuz docking to Salyut. For Mir, 7 out of 30 planned Soyuz automated dockings had to be completed manually due spacecraft or space station automated docking system problems. As of December 31, 2012, a Soyuz spacecraft has docked to ISS 44 times. Of those, 13 were performed manually, and 11 of those were relocations that are all done manually as part of nominal procedures.

The following list describes the relevant functions:

1) Launch Escape System – The launch escape system is automatic with no crew manual abort. The abort can be initiated from the ground by remote radio command by the launch director. The main events that would initiate an abort during launch are loss of control (detected by gyroscope sensors), premature booster stage separation (Stage 1), loss of pressure in the combustion chambers, lack of velocity, and loss of thrust (detected by weightlessness sensor). The escape system is activated and ready from 15 minutes before launch till escape rocket jettison at 115 seconds after launch. In the event of a launch-vehicle emergency, two signals are received by the crew module. A red booster emergency indicator and a central light illuminate and an intermittent audible alarm sounds. (Soyuz SAS)

2) Propulsion System – The Soyuz has three types of engines: the Orbital Maneuvering Engine (OME) with 3.1 kilonewtons force, the large thruster with 137 newtons force, and the small thruster with 24.5 newtons force. The propellant is nitrogen tetroxide as an oxidizer and unsymmetrical dimethylhydrazine as a fuel. The OME is the primary power plant for vehicle translation propulsion, issues correction burns for insertion into orbit, on-orbit burns during approach to the ISS, and initiating deorbit. The 14 large thrusters are used to effect both rotational and translational motion. They are mounted on the instrumentation propulsion module and transition section (between the propulsion module and the descent module). Their combined thrust serves as a backup to the OME if it fails. The 12 small thrusters are used to effect rotational motion only. They are divided into two groups of six mounted on the propulsion module and transition section. The crew has the capability to manually start and stop the propulsion system burns. (Soyuz Technology) (Soyuz)

3) Motion Control System (MCS) – The MCS is responsible for controlling trajectory and orientation vehicle motion. The MCS includes a digital loop, an analog loop, and a descent and entry control loop. The MCS provides automatic maneuvering and maintaining of spacecraft attitude, automatic execution and shutdown of the propulsion system engine burns, and automatic stabilization. The propellant is nitrogen tetroxide as an oxidizer and unsymmetrical dimethylhydrazine as a fuel. As a backup to the automatic system, the crew can interface with the MCS and manually perform these functions using the rotational hand controller installed to the right of the commander, the translation hand controller installed to the left of the commander, and the descent hand controller. (Soyuz Technology)

4) Automatic Rendezvous and Docking System – The orginal radar-based rendezvous system onboard Soyuz became known as Igla (Russian for “needle”). Later it was replaced with the more advanced Kurs (“course”) rendezvous system. The Kurs automatic rendezvous and docking system uses the variation in signal strength between antennas to compute relative positions, attitude, and approach rate. Once powered on by crew or ground command, the system operates automatically with commands from the onboard computer. The crew has the capability to manually rendezvous and dock if the Kurs fails. The Kurs-A, which uses five antennas, is being replaced with the Kurs-NA, which requires only one antenna and reduces the risk of docking failure, as only one antenna must be deployed and retracted. (Bushman and Hinman 1991) (Harding 2012)

5) Probe and Drogue Docking Mechanism – The docking mechanism probe motor and active hooks can be automatically operated by control commands generated by signals from sensors. The crew can monitor

and issue commands from the crew console to the docking mechanism. The docking mechanism can also be controlled by ground commands. (Soyuz Docking)

Missions 1, 2, and 3

The first crewed mission of the new spacecraft called Soyuz-1 had only one cosmonaut on board as it was considered a test flight. Not long after achieving orbit, failures occurred in the communications system, only one of two solar arrays deployed, and the primary maneuver control system failed. The cosmonaut was able to manually maneuver the spacecraft to the proper entry attitude. This manual capability would have allowed recovery of the spacecraft, except the parachute system (main and backup) failed to properly deploy, causing the loss of spacecraft and cosmonaut (System Failure Case Study: Tragic Tangle 2010). The second crewed Soyuz flight, Soyuz 3, was to rendezvous and dock with the crewed Soyuz 2, but failed to dock. The failed docking was blamed on manual control by the cosmonaut (piloting error) who repeatedly overrode the automatic docking system, and used nearly all of his orientation fuel in his first attempt to dock (Portree 1995) (Encyclopedia Astronautica: Soyuz 3).

Docking to Salyut

Soyuz 10 was to be the first spacecraft to dock to the first space station Salyut. On April 23, 1971 on orbit, the ionic sensors that were part of the automatic orientation system malfunctioned, and the crew manually took control. The approach for docking was automatic, with the Igla automatic rendezvous and docking system, but the Soyuz oscillated from side to side, so at 150 meters the commander took over and manually soft-docked to Salyut. The Soyuz control system was still active at capture, and the firing of attitude thrusters damaged the automatic docking system, preventing probe retraction for hard dock. This was a hardware or software design issue, as the Soyuz control system should have been disabled, allowing the spacecraft go to free-drift at docking system capture, referred to as soft dock. The crew was unable to release the capture latches, until the ground called up a procedure to provide an electrical signal to release the capture latches, as the signal was to be sent from Salyut. (Ivanovich 2008) (Encyclopedia Astronautica: Soyuz 10)

On June 7, 1971 the Soyuz 11 Igla automatic rendezvous and docking system was used during approach, but the commander took over manual control at 100 meters to complete the docking to Salyut. After successfully completing the mission on Salyut, the three crew members all died due to cabin depressurization that occurred when the descent module was separated from the orbital module during preparation for entry. (Ivanovich 2008)

Soyuz 15 was to conduct the second phase of crewed operations aboard the Salyut 3 military space station, but the Igla rendezvous system failed and no docking was made. The Soyuz had no propellant reserves for repeated manual docking attempts (Portree 1995) (Encyclopedia Astronautica: Soyuz 15). On Soyuz 21 the crew manually docked with the Salyut 5 station after failure of the Igla automatic docking system at the last stage of rendezvous. During preparation to return, the crew tried to undock, and the docking latches failed to release properly. As the jets were fired to move the spacecraft away, the docking mechanism jammed, resulting in Soyuz being undocked, but still attached to Salyut. The crew, using emergency procedures relayed from the ground, was able to finally disengage the latches (Encyclopedia Astronautica: Soyuz 21). During Soyuz 23 the sensors indicated an incorrect lateral velocity, causing unnecessary firing of the thrusters during rendezvous. The automatic system was turned off, but no fuel remained for a manual docking to the Salyut 5 space station (Portree 1995) (Encyclopedia Astronautica: Soyuz 23).

On Soyuz 33, the spacecraft was supposed to dock with a Salyut 6 station, but a failure of the main engine prevented rendezvous with the station and the mission was aborted. For the deorbit burn Mission Control Center – Moscow (MCC-M) commanded the reserve engines to turn on, and the commander had to do a manual shutdown, as the engine was firing longer than the required 188 seconds. The 25-second longer burn resulted in a high g ballistic entry.

During the first crewed flight of the new Soyuz T spacecraft, when the Soyuz T-2 mission was to dock with the Salyut 6 space station, the approach was completed automatically, but the new Argon computer failed, and the final 180 meters to docking were controlled manually. The Soyuz T-6 docking to Salyut 7 was completed manually when the spacecraft's automatic docking system failed. The Soyuz T-8 failed to dock with Salyut 7 due to a radar antenna boom that did not deploy, preventing automatic docking. With MCC-M permission the commander attempted a manual docking using only an optical sight and ground radar inputs, but had to abort to prevent a collision with Salyut. The Soyuz T-13 planned to manually dock with Salyut 7 since the station was unpowered due to station system failures. Manual docking was also performed on Soyuz T-15 due to loss of power on Salyut 7. The Salyut 7 station would have been lost had it not been for the manual docking capability of the Soyuz spacecraft. (Portree 1995)

Docking to Mir

The Salyut was replaced with the space station Mir. While the majority of the Soyuz dockings to Mir were performed in the automatic mode (23 of 34 Soyuz dockings), 11 dockings were performed in the manual mode. Of the 11, 3 were attributed to problems with the automatic system and 1 was due to errors in the Mir attitude control system. The other 7 manual dockings were either planned manual dockings (4) or the crew took over manual control due to perceived alignment issues with the automatic system (3).

Soyuz TM-5 started spinning after undocking from Mir due to human error, and the commander was able to stabilize the Soyuz quickly and depart. Just before the scheduled deorbit burn, the Soyuz orientation system failed, and when the engine did fire automatically the commander shut it down. The crew made a second attempt to deorbit, but the automatic system shut it down and started a countdown to separate the propulsion module. The commander was able to stop the countdown, and later the deorbit burn was good. On Soyuz TM-8 when the Kurs rendezvous and docking system malfunctioned at 4 meters, the commander took over manual control and docked to Mir. The Soyuz TM-17 collided twice with the Mir while maneuvering close to Mir to photograph the Androgynous Peripheral Attach System (APAS) docking system. The cause of the collision was identified as a crew switch error. When the hand controller in the Soyuz Orbital Module was turned on, it disabled the Soyuz descent module hand controller the commander was using to control the Soyuz. On Soyuz TM-20 the on-board spacecraft computer failed at 130 meters from the Mir, and the crew finished the docking under manual control (Encyclopedia Astronautica: Mir EO-16). During the Soyuz TM-25 mission the Kurs automatic system failed at 5 meters from the Mir, and the crew finished the docking under manual control (Encyclopedia Astronautica: Mir EO-23). On Soyuz TM-26 the commander saw a slight upward deviation in the Kurs automatic system close to the Mir, and he finished the docking under manual control. (Note: another report suggests the automatic system performance was within specifications, and that the commander's decision to take over control was motivated by the cosmonaut pay structure which pays bonuses for successful manual dockings.) (Encyclopedia Astronautica: Mir EO-24) On Soyuz TM-28 the MCC-M told the commander to take control manually at a distance of 20 meters due to concerns with the Kurs automatic system, and the commander docked to Mir manually (Encyclopedia Astronautica: Mir EO-25). On Soyuz TM-30 the crew saw a deviation of one or two degrees at nine meters from Mir, and the commander took over manually to approach and dock to Mir (Encyclopedia Astronautica: Mir EO-28). (Portree 1995)

Docking to ISS

As of December 31, 2012, a Soyuz spacecraft has docked to ISS 44 times. Of those, 13 were performed manually, and 11 of those were relocations that are all done manually as part of nominal procedures. The other 2 manual dockings occurred on TMA-5 and TMA-14 and were due to problems with the automatic system which required the crew to dock manually with ISS (Soyuz TMA-5) (Soyuz TMA-14).

During the Soyuz TMA-5 approach to the ISS docking port, at a relative range of approximately 47 meters, a Soyuz thruster failed, which triggered an automatic abort. Under direction from MCC-M the Soyuz commander took over manual control of the Soyuz spacecraft, and the docking was completed in manual mode. During the Soyuz TMA-14 fly-around prior to final approach and docking, the Soyuz automatic system sensed a thruster failure and initiated an automatic abort. The Soyuz commander was directed by MCC-M to take over manual control of the spacecraft, then confirmed proper thruster operation and completed the docking in manual mode. In both these cases manual crew control capability saved the mission. Table 3 provides a summary of Soyuz manual crew control events which could have resulted in loss of mission or loss of crew (worst case) had manual control capability not been incorporated into the design.

Table 3. Summary of Soyuz Missions for Which Manual Control was Necessary to Prevent LOC or LOM

Russian Programs	Number of Missions	Number (and Percentage) of Missions Requiring Crew Control to Prevent LOC or LOM		
		LOC	LOM	Total
Soyuz	40	3	1	4 (10%)
Soyuz T	15	0	1	1 (7%)
Soyuz TM	34	2	7	9 (26%)
Soyuz TMA	21	0	3	3 (14%)
Soyuz TMA Digital	7	0	1	1 (14%)
Total (Soyuz TM, TMA, and Digital)	62	2	11	13 (21%)
Total (All)	117	5	13	18 (15%)

Progress

Manual Control Capability

Due to the criticality of space station resupply, the Russians provided a manual capability to dock the Progress spacecraft to the Mir and ISS space stations. This manual capability is called TORU (Teleoperator Control System), and functions as a backup to the automated Kurs rendezvous and docking system.

Docking to Mir

The uncrewed Progress cargo spacecraft used the Kurs automated rendezvous and docking system developed to deliver cargo, consumables, and propellant to the Mir space station. As a contingency back-up capability the Mir crew could use the TORU to remotely pilot and dock the Progress spacecraft if the Kurs automatic system failed.

There were a total of 53 Progress dockings (or attempted dockings) with Mir. Of the 53 dockings, six were performed in manual mode (the MIR crew piloted Progress remotely).

Of those six manual dockings, three were planned manual dockings to relocate the Progress vehicle to another port and/or to test TORU equipment, and three were contingency manual dockings due to system failures (M-24, M-35 redock, and M-38). Of the six manual dockings, four were successful in docking the Progress spacecraft to MIR, while two failed. One of these failures resulted in a collision with the Mir station (M-34). In both the failed manual dockings the Russian commander did not have sufficient information and training to make a successful docking.

For the first attempt of a long-range test of TORU during Progress M-33 re-docking, the crew was unable to control the spacecraft due to inadequate relative navigation cues and poor video imagery of the approaching Progress spacecraft, so the docking was aborted. For the second long-range test of the TORU, the Kurs system was turned off, which prevented the commander from receiving the critical range and range rate data, and the Progress M-34 collided with the Mir Spektr Module (Encyclopedia Astronautica: Mir EO-23). Both are examples of the fact that for manual control to be successful, the crew must have sufficient training and information to perform the required task.

The four successful manual dockings were Progress M-16 re-dock (first TORU manual docking test), M-24, M-35 re-dock, and M-38. The M-24 and M-38 were performed manually due to a Kurs failure (Encyclopedia Astronautica: Mir EO-16) (Encyclopedia Astronautica: Mir EO-25). M-35 was the result of a Mir computer failure (Encyclopedia Astronautica: Mir EO-24).

Docking to ISS

As of December 31, 2012, there have been 52 Progress spacecraft dockings to the ISS. Of those, seven dockings were performed manually by the ISS crew using the TORU system, all of which were successful in docking the Progress spacecraft to ISS. Five of the seven manual dockings were due to problems with the Kurs automatic system or Progress Motion Control System (Progress M1-4, M-01M, M-67, M-05M, and M-08M). One was due to the loss of a Russian ground control station (Progress M-53), and one was a nominally planned manual docking to relocate a Progress spacecraft to another port (Progress M1-4 redock).

During the Progress M-58 docking, the Kurs-A antenna failed to retract. MCC-M issued a command to retract the antenna and the docking mechanism automatic sequence halted. MCC-M instructed the crew to manually re-extend the Progress docking probe using the TORU, to increase the clearances between the ISS and Progress, while ground controllers performed troubleshooting of the failed antenna and assessed docking clearances. The probe was subsequently retracted in small increments by the MCC-M to achieve a ready-to-latch configuration. The ISS crew, at the request of MCC-M, due to loss of communications with the Russian ground station, then manually closed the Service Module active hooks for hard docking using the Russian Segment laptop computer. This crew commanding ability allowed the ISS to resume attitude control and resume nominal operations following an extended period in free drift (~3.5 hours) with moderate load shedding. The Progress latches were commanded closed by the MCC-M on a subsequent ground pass.

Given that roughly 14% (7 out of 51) of Progress automatic dockings were not successful (all were completed successfully in manual mode), the high cost involved with spacecraft launches and the importance of the cargo resupply to the space station, the value of manual crew control back-up capability to dock Progress vehicles cannot be overlooked or underestimated.

5 Observations and Recommendations: Manual Control Considerations

Of the 71 significant crew manual control events identified in this report, 35 events could have resulted in loss of mission, had crew manual control capabilities not been available to support continued mission operations. Nineteen events could have resulted in loss of crew if manual control capabilities were not available. Eighteen events were caused by human error, inadequate human-system interfaces, and/or inadequate training which put the crew and/or mission at risk. Lessons learned regarding these events can help inform the decisions regarding when and how to implement manual crew control capabilities in future spacecraft designs. Table 1, shown in the Executive Summary and repeated below, summarizes manual crew control capabilities for each human spaceflight program and how those capabilities were used.

Table 1. Summary of Manual Control Capabilities, by Program (repeated from the Executive Summary)

Capability		Program				
		Mercury	Gemini	Apollo	Space Shuttle	Soyuz
Pre-launch/Ascent	Abort Initiation	✓	✓	✓	✓	X
	Abort Inhibit	X	✓	✓	✓	X
	Manual Steering	X	X	✓ (2nd & 3rd stage)	✓ (post MET 1:30)	X
	Manual Throttling and Shutdown	X	X	✓ (3rd stage)	✓	X
On Orbit	Abort Initiation	✓	✓ C	✓	✓	✓ C
	Attitude Control	✓ C N	✓ C N	✓ C N	✓ C N	✓ C
	Translation Burns		✓ N	✓ N	✓ N	✓ C
	Rendezvous		✓ C	✓ N	✓ N	✓ C
	Docking/Undocking		✓ N	✓ N	✓ N	✓ C N
Lunar Descent/ Ascent	Abort Inititation			✓		
	Abort Inhibit			✓		
	Attitude Control			✓ C N		
	Translation Burn			✓ C N		
Entry/Landing	Attitude Control	✓ C	✓ C	✓ C	✓ N	✓ C
	Parachute Deployment	✓ C	✓	✓ C	✓ N (drag chute)	X
	Landing Gear Deployment				✓ N	
	Runway Steering				✓ N	

✓ Manual capability was provided
- **N** - used for nominal operations
- **C** - used in a contingency event

X Manual capability was NOT provided

(shaded) Capability not applicable to the program

The following key considerations should be used to help determine when and how to implement manual crew control capabilities:

1) **Is the function critical for crew safety or primary mission objective?**

   Sometimes engineers or end users have a tendency to add extra crew control features to the design to "enhance" its operational flexibility. Although their intentions are good, these added features drive cost up, impact Design, Development, Test, and Evaluation (DDT&E) schedules and crew training requirements, and may actually introduce new, unanticipated risks to crew safety or mission success by introducing new failures or hazard scenarios. As a result, crew manual override capabilities should focus on functions necessary to protect the crew and primary mission objective in the event of a failure or anomaly. System safety analysis and reliability analyses will help identify these critical functions and failure scenarios during the early DDT&E phase of the program.

   The following flights are examples of instances in which manual crew control either saved the crew or primary mission following loss of a critical function: Mercury MA-6, MA-7, and MA-9, Gemini 4, 8, and 12, Apollo Lunar Module landings, Apollo Soyuz Test Project, Skylab 2 and 4, STS-32, Vostok 6, Voskhod 2, Soyuz 1*, 11, 21, T-2, T-6, 33,T-13, T-15, TM-5, TM-8, TM-20, TM-25, TM-26, TM-28, TM-30, TMA-5, and TMA-14.
   *Soyuz 1 crew member lost due to subsequent failures.

2) **Is the time requirement to perform the function well within the normal human response time and performance envelope, considering the off-nominal environment due to automatic control system failure?**

   Any proposed crew manual control capabilities should be evaluated from a human factors standpoint to ensure the crew can effectively utilize the control capability in the expected environment. Given the dynamic and harsh environments associated with spaceflight and the high energy systems involved, conditions can degrade rapidly on a launch vehicle or spacecraft following a failure. In some cases the time to catastrophic effect (loss of vehicle, loss of life) can be only seconds. Failures may also result in induced environments such as excessive g-forces which could incapacitate or otherwise prohibit the crew from taking necessary action to mitigate the effects of the failure. For these reasons many of the contingency responses to failures must be automated and not rely solely on the crew to take action.

   A good example of this is the automated emergency ascent abort systems used by NASA and the Russian vehicles to detect catastrophic failures and initiate aborts to protect the crew. However, it should be noted that on STS-51F a high risk ascent abort was averted and the mission was saved by having the capability to inhibit automatic main engine shutdown after multiple main engine temperature sensor failures.

3) **Is the crew monitoring of the automatic system sufficient to ensure it can seamlessly enter the control loop?**

   On STS-3 the final transition from autopilot to crew manual control was delayed to test the orbiter automatic landing capabilities. This late transition did not allow the commander sufficient time to get a feel for the vehicle handling characteristics prior to landing, which involves relatively complex flare and derotation maneuvers. This late transition, combined with atmospheric conditions at the alternate landing site, resulted in a hard, fast landing and pilot-induced oscillations during derotation. Procedures were subsequently changed to ensure the commander had sufficient time at controls prior to critical landing operations.

During an X-15 flight an electrical disturbance caused the deactivation of the automatic reaction control system, forcing the pilot to take over manual control of the aircraft. After assuming control of the aircraft, the pilot misinterpreted the aircraft attitude data and lost control of the aircraft. The lack of situational awareness and ability of the pilot to resume control of the aircraft resulted in the loss of the aircraft and pilot. To avoid this type of fatal incident in the future, designers should ensure the flight crew has sufficient insight into the performance and status of the vehicle and critical systems.

4) Is sufficient information available to the crew to successfully perform the function?

The collision of the Progress M-34 spacecraft with the space station Mir was attributed in part to the lack of sufficient relative navigation cues and poor video imagery. This potentially catastrophic event could have been prevented if the commander had critical range and range rate data and better video imagery from the approaching Progress spacecraft.

5) Are there sufficient controls or inhibits in place to preclude inadvertent engagement of manual override capabilities?

Crew controls need to be readily accessible to the crew in the event of an emergency. However, when implementing manual crew controls it is important to include safeguards to preclude inadvertent activation when inadvertent activation could create a hazard (compromise crew safety or mission success). There were a number of cases in which the shuttle crew inadvertently deactivated the auto pilot and engaged the manual control stick steering by bumping the hand controller during entry preparations. Fortunately, these events were detected and resolved quickly by ground or flight crew without incident, but they did highlight a vulnerability in the design. System safety and human factors analysis should include assessments of manual back-up capability.

During the Apollo 10 mission the crew inadvertently engaged the automatic guidance system which caused the spacecraft to pitch and yaw wildly until the crew jettisoned the lunar descent module and regained control of the spacecraft in manual control mode.

6) Is the crew trained/refreshed in the operation on a regular basis?

Crew error and lack of sufficient training were contributing factors in several significant human spaceflight events, including the MA-7 excessive propellant usage, the Skylab 4 issue with opening the Stabilization Control System circuit breakers, certain ASTP hard docking and entry anomalies, the Soyuz TM-17 collision with Mir, the Progress M-34 collision with Mir, the STS-9 GPC restring error during landing, the STS-32 state vector uplink error, the STS-37 low energy landing, and the STS-90 hard landing. Advances in high fidelity ground simulations have greatly improved the quality of flight crew training and have helped to reduce the occurrence of human errors during crewed spaceflight missions. Crew training should include both nominal and off-nominal operational scenarios where crew can practice and become proficient in executing malfunction procedures including the use of contingency crew control capabilities. Long duration missions will require refresher training be performed on board the spacecraft during the mission to ensure critical skills are retained and refreshed prior to critical operations.

7) Is the overall function reliability improved for crew safety and mission success with manual control, taking into account human reliability and mission duration impact?

When considering crew manual control, the risk of crew error must be taken into account, as past experience of both NASA and Russian programs has shown that crew error has caused the loss of critical automatic systems in some cases. Examples of this are ASTP and Skylab 4. In contrast, for each of these missions, having a manual capability allowed for the crew to recover control and save the spacecraft. Lack of training and human factors were major contributors to the crew error during the Skylab 4 mission. For the Russians on Soyuz TM-5 undocking from Mir, crew error caused loss of control, but the crew was able to recover and return safely. The Soyuz TM-17 collided twice with the Mir when moving close to photograph the APAS docking system, due to a crew switch error. Crew error while controlling Progress M-33 caused a near miss of hitting the Mir.

The Russians, who track crew errors on all their missions, have stated that 10% to 15% of all spacecraft problems were caused by crew error. To mitigate the risk of human error on future crewed spaceflight missions, system safety and human error analysis (required by NPR 8705.2, *NASA Human Rating Requirements*) should be performed to evaluate the potential for human error during nominal and off-nominal operations and ensure proper controls are in place to mitigate the risk to crew and primary mission objectives.

8) Does the overall risk benefit trade study support implementation of manual override capabilities when considering technical, cost, and schedule impacts?

The increasing use of probabilistic risk assessments has supported trade studies and characterized the risk benefits of implementing certain design features such as back-up manual control capabilities. However, the risk benefits associated with any proposed back-up manual control also need to be weighed against programmatic resources (cost) and constraints (technical performance, schedule) in order to support a design decision. Failure to do so could result in a safe design that bankrupts the program or is too heavy to fly.

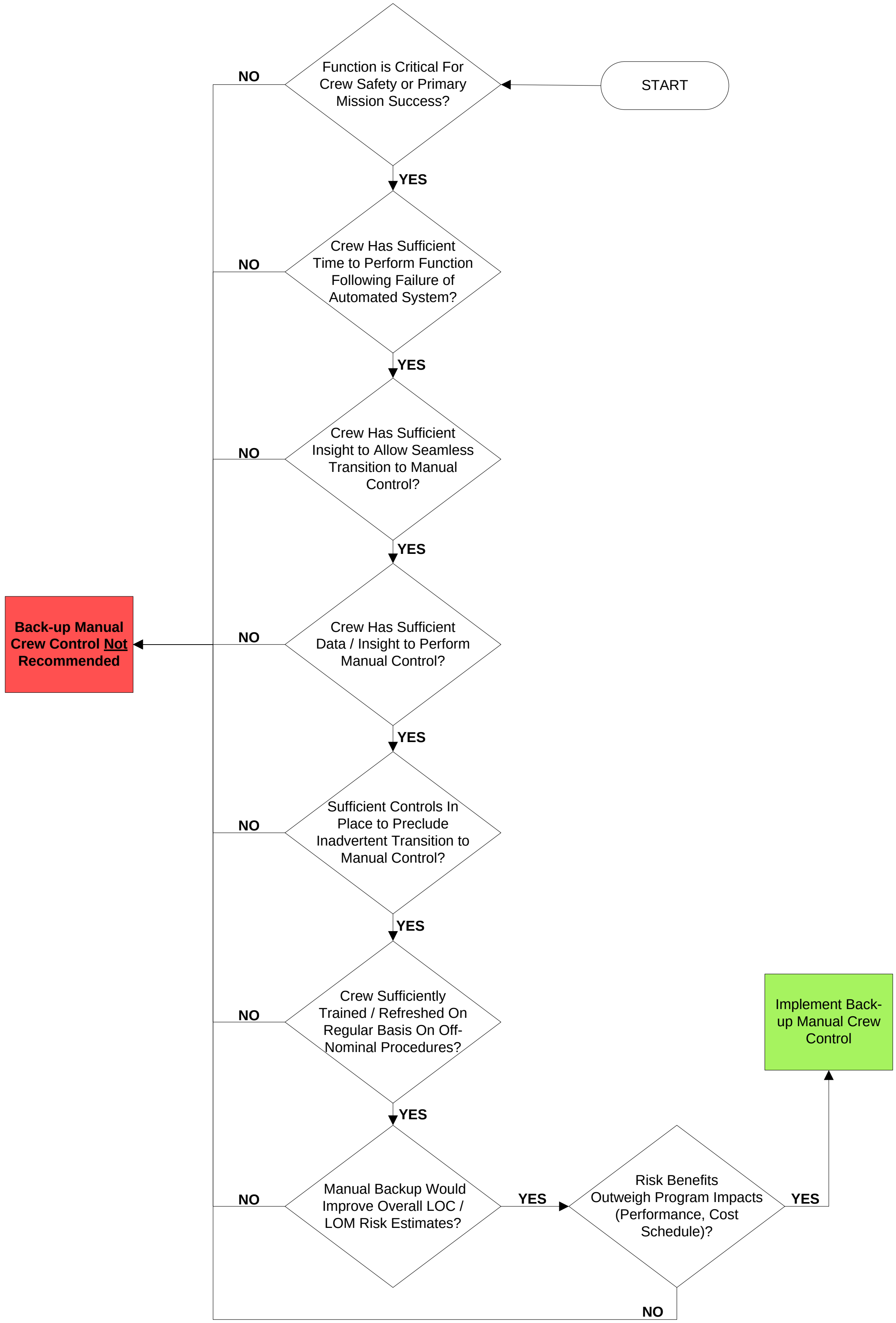

Figure 1. Flow Chart for Key Considerations

6 Conclusions

An analysis of flight history reveals that manual crew control backup for automated systems has the potential to save the crew and/or mission when in-flight anomalies occur. However, the addition of manual crew control capabilities comes at the expense of budget and schedule, and can introduce new risks associated with potential human error. Risk benefit trades must be performed to determine what types of manual crew control capabilities should be incorporated into new spacecraft designs to mitigate risks to flight crew and mission success while staying within programmatic constraints.

This report summarized the flight history of both U.S. and Russian programs and analyzed this information to produce several key considerations to be taken into account when determining when and how to implement back-up manual crew control capabilities. These key considerations are based on past human spaceflight experiences and lessons learned. This work is intended to assist current and future spacecraft designers in determining the optimal mix of automated and manual control.

Acronyms

AC	Alternating Current
ACME	Attitude Control Maneuver Electronics
AGS	Abort Guidance System
APAS	Androgynous Peripheral Attach System
ASCS	Automatic Stabilization Control System
ASTP	Apollo-Soyuz Test Project
CM	Command Module
CSM	Command and Service Module
DAP	Digital Auto Pilot
DDT&E	Design, Development, Test, and Evaluation
EDS	Emergency Detection System
ELS	Earth Landing System
FSO	Flight Safety Office
GPC	General Purpose Computer
LES	Launch Escape System
LM	Lunar Module
LOC	Loss of Crew
LOI	Lunar Orbit Insertion
LOM	Loss of Mission
MA	Mercury Atlas
MCC	Mission Control Center
MCC-M	Mission Control Center – Moscow
MCS	Motion Control System
MDS	Malfunction Detection System
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirement
OAMS	Orbital Attitude and Maneuver System
OME	Orbital Maneuvering Engine
PGNS	Primary Guidance and Navigation System
RCS	Reaction Control System
RMS	Remote Manipulator System
RRS	Retrograde Rocket System
S&MA	Safety and Mission Assurance
SCS	Stabilization Control System
SM	Service Module
SPS	Service Propulsion System
SSME	Space Shuttle Main Engine
TORU	Teleoperator Control System
U.S.	United States

References

Jones, Eric M., ed. *Apollo 12 Lunar Surface Journal.* 1995. http://www.hq.nasa.gov/office/pao/History/alsj/a12/a12.html (accessed November 27, 2012).

Bushman, David M, and Elaine M Hinman. *Soviet Automated Rendezvous and Docking System Overview.* NASA, 1991.

Carpenter, M. Scott, et al. *We Seven.* New York: Simon & Schuster, 1962.

"Columbia Accident Investigation Board Report, Volume 1." August 2003.

Compton, W. David, and Charles D Benson. *NASA SP-4208, Living and Working in Space: A History of Skylab.* Washingto D.C.: NASA, 1983, 271.

Encyclopedia Astronautica: Apollo 10. http://www.astronautix.com/flights/apollo10.htm (accessed October 5, 2012).

Encyclopedia Astronautica: Gemini 12. http://www.astronautix.com/flights/gemini12.htm (accessed October 5, 2012).

Encyclopedia Astronautica: Gemini 5. http://www.astronautix.com/flights/gemini5.htm (accessed October 5, 2012).

Encyclopedia Astronautica: Mercury MA-7. http://www.astronautix.com/flights/merryma7.htm (accessed October 5, 2012).

Encyclopedia Astronautica: Mercury MA-9. http://www.astronautix.com/flights/merryma9.htm (accessed October 5, 2012).

Encyclopedia Astronautica: Mir EO-13. http://www.astronautix.com/flights/mireo13.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Mir EO-16. http://www.astronautix.com/flights/mireo16.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Mir EO-23. http://www.astronautix.com/flights/mireo23.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Mir EO-24. http://www.astronautix.com/flights/mireo24.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Mir EO-25. http://www.astronautix.com/flights/mireo25.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Mir EO-28. http://www.astronautix.com/flights/mireo28.htm (accessed October 11, 2012).

Encyclopedia Astronautica: Soyuz 10. http://www.astronautix.com/flights/soyuz10.htm (accessed November 2012, 28).

Encyclopedia Astronautica: Soyuz 15. http://www.astronautix.com/flights/soyuz15.htm (accessed November 2012, 28).

Encyclopedia Astronautica: Soyuz 21. http://www.astronautix.com/flights/soyuz21.htm (accessed November 28, 2012).

Encyclopedia Astronautica: Soyuz 23. http://www.astronautix.com/flights/soyuz23.htm (accessed November 28, 2012).

Encyclopedia Astronautica: Soyuz 3. http://www.astronautix.com/flights/soyuz3.htm (accessed November 28, 2012).

Encyclopedia Astronautica: Voskhod 1. http://www.astronautix.com/flights/voskhod1.htm (accessed January 23, 2013).

Encyclopedia Astronautica: Vostok. http://www.astronautix.com/craft/vostok.htm (accessed January 23, 2012).

Ezell, Edward Clinton, and Linda Neuman Ezell. *NASA SP-4209, The Partnership: A History of the Apollo-Soyuz Test Project.* Washington D.C.: NASA, 1978, 340-349.

Godwin, Robert, ed. *Apollo 10: The Nasa Mission Reports.* Burlington, Ontario: Apogee Books, 1971.

Grimwood, James M., and Barton C. Hacker. *NASA SP-4230, On the Shoulders of Titans: A History of Project Gemini.* NASA Document, NASA, 1977.

Harding, Pete. *Progress M-15M Re-docks to ISS Following Resolution of Kurs-NA Failure.* July 28, 2012. http://www.nasaspaceflight.com/2012/07/progress-m-15m-re-docks-iss-kurs-na/ (accessed March 6, 2013).

Hitt, David, Owen Garriott, and Joe Kerwin. *Homesteading Space: The Skylab Story.* Lincoln: University of Nebraska Press, 2008.

"IDRD Flight History Summary." *Flight Program Integration Panel.* November 20, 2012. https://iss-www.jsc.nasa.gov/nwo/mio/riit/fpwg/web/FPIP2.shtml (accessed November 29, 2012).

Ivanovich, Grujica S. *Salyut - The First Space Station: Triumph and Tragedy.* Chichester: Praxis Publishing Ltd., 2008.

Jenkins, Dennis R. *NASA SP-2000-4518, Hypersonics Before the Shuttle: A Concise History of the X-15 Research Airplane.* NASA, 2000, 61.

JSC Automatic Rendezvous and Docking Working Group. 2008. http://mod.jsc.nasa.gov/dm/a-team/ar&d/ar&d.htm (accessed January 16, 2013).

JSC Mission Operations Directorate Anomaly Report Database. January 16, 2013.

JSC Mission Operations Directorate Knowledge Base Database. January 16, 2013.

JSC-08053, Skylab 1/2 Technical Crew Debriefing. NASA, June 30, 1973, 4-12, 13.

JSC-08809, Skylab 1/4 Technical Crew Debrief. NASA, February 22, 1974, 9-19, 9-26.

JSC-09823, ASTP Technical Crew Debriefing. NASA, August 8, 1975, 4-26, 4-27, 5-4, 5-5.

JSC-10638, Apollo Soyuz Mission Anomaly Report No. 1: "Toxic Gas Entered Cabin During Earth Landing Sequence". NASA, December 1975.

Leonov, Alexei. "The Nightmare of Voskhod 2." *Air and Space Magazine*, January 2005.

"Lessons Learned Entry 0194: Space Shuttle Automatic Landing Capabilities." *NASA Engineering Network: Lessons Learned.* June 6, 1994. https://nen.nasa.gov/web/ll/home/llis-doc-viwer?url=https://nen.nasa.gov/llis_content/0194.html (accessed January 7, 2013).

NASA JSC-07904, Apollo 17 Mission Report. NASA, March 1973, 10-11.

NASA MSC-00171, Apollo 11 Mission Report. NASA, November 1969, 5-4, 5-5.

NASA MSC-01540, Analysis of Apollo 12 Lightning Incident. NASA, February 1970.

NASA MSC-02682, Apollo 13 Mission Report. NASA, September 1970.

NASA MSC-04112, Apollo 14 Mission Report. NASA, May 1971, 9-7.

NASA MSC-05161, Apollo 15 Mission Report. NASA, December 1971, 9-8.

NASA MSC-07230, Apollo 16 Mission Report. NASA, August 1972, 9-19.

NASA MSC-G-R-61-1, Gemini Program Misson Report: Gemini 12. NASA, January 1967.

NASA/TM-2011-216142, Space Shuttle Missions Summary. NASA, September 2011.

NPR 8705.2B, Human-Rating Requirements for Space Systems. NASA Procecural Requirement, NASA, August 2012.

NSTS 37420 STS-90, Space Shuttle Mission Report. NASA, June 1998, 35.

O'Connor, Bryan. "A Gift: Lesson and Analogies from STS-3 Close Call." Safety & Mission Assurance, NASA, May 1, 2006.

Peters, Jeff. "Significant NASA Spaceflight Events and Lessons Learned." presentation, Space Shuttle Program, Space Shuttle S&MA Office, NASA, May 12, 2005, 3, 6-7, 20.

Portree, David S. F. "NASA RP-1357, Mir Hardware Heritage." 1995.

Results of the First U.S. Manned Orbital Space Flight. Manned Spaceflight Center NASA, February 20, 1962, 121.

Scott, David, and Alexei Leonov. *Two Sides of the Moon: Our Story of the Cold War Space Race.* New York: St. Martin's Press, 2004.

SEDR 104-18, Project Mercury Familiarization Manual. NASA/McDonnell, 1962.

SEDR 300 Volume 1, Project Gemini Familization Manual. NASA/McDonnell, December 31, 1964.

Soyuz. http://www.braeunig.us/space/specs/soyuz.htm (accessed March 6, 2013).

Soyuz Docking. http://www.russianspaceweb.com/docking.html (accessed March 6, 2013).

Soyuz SAS. http://www.russianspaceweb.com/soyuz_sas.html (accessed March 6, 2013).

Soyuz Technology. http://www.russianspaceweb.com/soyuz_tech.html (accessed March 6, 2013).

Soyuz TM-17. http://www.russianspaceweb.com/mir_close_calls.html (accessed October 11, 2012).

Soyuz TMA-02. http://www.russianspaceweb.com/iss_soyuz_tma02m.html (accessed October 11, 2012).

Soyuz TMA-14. http://www.russianspaceweb.com/iss_soyuztma14.html (accessed October 11, 2012).

Soyuz TMA-18. http://www.russianspaceweb.com/iss_soyuztma18.html (accessed October 11, 2012).

Soyuz TMA-5. http://www.russianspaceweb.com/iss_soyuztma5.html (accessed October 11, 2012).

Spacecraft: Manned: Mir: Close Calls. http://www.russianspaceweb.com/mir_close_calls.html (accessed October 11, 2012).

Spacecraft: Manned: Progress. http://www.russianspaceweb.com/progress.html (accessed October 11, 2012).

Spacecraft: Manned: Progress: M-M. http://www.russianspaceweb.com/progress_m_0m.html (accessed October 11, 2012).

SPACEWARN Bulletin Number 526. August 25, 1997. http://nssdc.gsfc.nasa.gov/spacewarn/spx526.html (accessed November 28, 2012).

Stafford, Thomas P. *We Have Capture.* Washington D.C.: Smithsonian Institution Press, 2002.

"STS-32: Uplink Error Caused Vehicle Attitude Change." Close Call Awareness Paper, Space Shuttle Program, April 25, 2005.

Swenson, Loyd S., James M. Grimwood, and Charles C. Alexander. "NASA SP-4201, This New Ocean: A History of Project Mercury." NASA Document, 1989, 472.

"System Failure Case Study: Tragic Tangle." (NASA Safety Center) 4, no. 6 (June 2010).

USA007587, Shuttle Crew Operations Manual. NASA/United Space Alliance, October 15, 2004.

Appendix A: Summary Table for Significant Events – U.S. Programs

The table below categorizes the worst case potential consequence of failure for each anomaly as either loss of crew or loss of mission in most cases. Not all of these incidents counted toward the metrics described in the report. The loss-of-crew metrics in the report reflect only those instances in which the lack of manual control would have meant the loss of the crew. If an incident in the table is categorized as a potential loss-of-crew event, it means that loss of crew was the worst possible consequence of that anomaly.

Mission	Anomaly	Worst Case Potential Consequence Of Failure	Crew Response
Mercury MA-6	Yaw reaction jet failure caused attitude control problem on orbit.	LOC	Astronaut took over manual control to regain control of the spacecraft. He used fly-by-wire control for on-orbit and entry capsule control. He later manually changed entry procedures following instructions from Mercury Control to keep the retropack attached during entry.
Mercury MA-7	Spacecraft automatic control system experienced problems prior to de-orbit burn, resulting in an incorrect attitude for de-orbit burn.	LOC	Crew member switched to manual control to re-orient spacecraft for de-orbit burn; however, crew error in yaw positioning resulted in an overshoot of the planned landing site.
Mercury MA-7	Early RCS fuel depletion (occurred 70,000 to 80,000 feet altitude) due to excessive control inputs from astronaut during on-orbit operations resulted in excessive capsule motion and rates during entry.	LOC	Crew member had to manually deploy drogue chute early to stabilize the capsule during entry (26k vs. 21k feet).
Mercury MA-9	Automatic control system failed due to electrical short.	LOC	Astronaut had to use manual control to deorbit and control the spacecraft.
Gemini 4	Spacecraft computer failure.	LOC	Crew had to perform a manual rolling entry.
Gemini 5	Computer programming error.	Delayed recovery of crew.	Crew had to take manual control to minimize landing point error.

Gemini 8	RCS jet failed *on* due to a short to ground.	LOC	Crew had to manually select the entry RCS system to regain spacecraft control.
Gemini 12	Automatic rendezvous mode failed.	LOM	Crew used manual backup rendezvous capability to dock with the Agena target vehicle.
X-15 Flight	Electrical disturbance deactivated the automatic RCS system.	LOC	Pilot took over manual control of the aircraft, but misinterpreted the attitude indicator and made a yaw input instead of roll, increasing the aircraft deviation. Adaptive control system became saturated preventing pilot from regaining control.
Apollo 10	During LM rendezvous with CSM in lunar orbit, commander in spacesuit inadvertently hit the Abort Guidance System switch, moving it from Hold Attitude to Auto. This caused the LM to suddenly start looking for the CSM and the LM suddenly flipped end over end.	LOC	Commander grabbed the attitude controller and switched to manual, jettisoned the Descent Stage, and regained control of the LM. Crew then rendezvoused and docked with the CSM.
Apollo 11	LM PGNS targeting for an area too rough to land.	LOM	Commander took over semi-automatic control manually to avoid the rough (boulders and craters) landing area.
Apollo 12	LM PGNS targeting for an area too rough to land.	LOM	Commander took over semi-automatic control manually to avoid the rough (boulders and craters) landing area.
Apollo 14	LM PGNS targeting for an area too rough to land.	LOM	Commander took over semi-automatic control manually to avoid the rough (boulders and craters) landing area.
Apollo 16	LM PGNS targeting for an area too rough to land.	LOM	Commander took over semi-automatic control manually to avoid the rough (boulders and craters) landing area.
Apollo 17	LM PGNS targeting for an area too rough to land.	LOM	Commander took over semi-automatic control manually to avoid the rough (boulders and craters) landing area.
Apollo 12	During ascent, spacecraft was struck twice by lightning, causing loss of CSM fuel cell power, AC power, and spacecraft computer.	LOM	Crew was able to manually regain CSM electrical power and continue the mission.

Apollo 13	During trans lunar coast the Service Module oxygen tank exploded, causing loss of CSM oxygen and fuel cell power.	LOC	Complete power-down of the CSM and major power-down of LM resulted in manual crew control of CSM/LM spacecraft, using the LM systems.
Apollo 15	LM PGNS targeting for an area outside the pre-selected landing area.	LOM	Commander took over semi-automatic control manually to land in the pre-selected landing area.
Skylab 2	Unable after many CSM docking attempts to obtain capture (soft dock) with the Skylab space station.	LOM	Crew had to use a manual backup procedure to bypass the capture interlock and manually retract the docking probe, then thrust the CSM forward to trip the docking latches achieving hard dock.
Skylab 4	After 3 months on orbit, during entry preparation, crew opened Stabilization and Control System Pitch and Yaw Circuit Breakers (CB) instead of Service Propulsion System Pitch and Yaw CBs, causing loss of CM automatic RCS control at CSM separation.	LOC	After CSM separation the CM was apex forward. The crew selected manual RCS control to get into the proper attitude, aft heatshield forward, for entry.
ASTP (Apollo Soyuz Test Project)	During the second docking the CSM/Docking Module was misaligned and hit the Soyuz docking system very hard, almost to the Soyuz docking system design limits.	LOM	CM Pilot continued the docking even though he had poor docking target visibility and washout of the crew member optical alignment sight reticle.
ASTP	During CM entry/landing the crew failed to enable the automatic Earth Landing System. Toxic N_2O_4 was sucked into the cabin when RCS propellant dump occurred with cabin relief valve open.	LOC	The crew recognized they were below the deployment altitude and had to manually perform the ELS functions, jettison the apex cover, deploy the drogue chutes, and deploy the main chutes.
STS-3	During landing the autopilot was engaged and a pilot-induced oscillation occurred during landing derotation.	LOC	Commander disconnected the autopilot and touched down manually.

STS-9	During landing GPC-2 failed and avionics reconfiguration by the Pilot resulted in loss of the Flight Control System.	LOC	After GPC-2 failed, the pilot performed an avionics reconfiguration based on a normal configuration. The configuration had been changed earlier due to GPC-1 failure, there was no display showing this to the pilot, and this resulted in an erroneous reconfiguration causing loss of FCS.
STS-32	MCC up-linked an erroneous state vector to the FCS, causing FCS to fire RCS jets, and orbiter to start to spin up.	LOC	MCC called to wake up the crew. The crew was able to take manual control and stop the RCS jets firing and orbiter spin up.
STS-37	Orbiter landed 623 feet short of runway threshold.	LOC	Commander had misinterpreted the indications of low energy around the hack as high energy and high winds, resulting in a low energy landing.
STS-90	Orbiter landed hard and fast.	LOC	Piloting errors coupled with rogue wind gusts.
Several Shuttle Missions	Auto DAP inadvertently disengaged by crew when crew bumped control stick during entry operations.	LOC	Ground and/or flight crew detected auto DAP disengagement and re-engaged DAP without incident.

Appendix B: Summary Table for Significant Events – Russian Programs

The table below categorizes the worst case potential consequence of failure for each anomaly as either loss of crew or loss of mission in most cases. Not all of these incidents counted toward the metrics described in the report. The loss-of-crew metrics in the report reflect only those instances in which the lack of manual control would have meant the loss of the crew. If an incident in the table is categorized as a potential loss-of-crew event, it means that loss of crew was the worst possible consequence of that anomaly.

Mission	Anomaly	Worst Case Consequence of Failure	Crew Response
Vostok 2	Unknown – insufficient data.		Crew member used manual orientation to control spacecraft on orbit.
Vostok 3/4	Unknown – insufficient data.		Joint mission; both crew members used manual orientation on-orbit.
Vostok 6	Following on-orbit insertion the spacecraft was mis-oriented 90 degrees from the intended orientation due to the automatic system being set-up incorrect.	LOC	Prior to entry the crew member used manual control to properly orient the spacecraft for entry.
Voskhod 2	The spacecraft automatic guidance system malfunctioned prior to de-orbit burn.	LOC	The crew member switched off the automatic system and performed spacecraft orientation and de-orbit burn manually.
Soyuz 1	Not long after achieving orbit, failure of the primary maneuver control system.	LOC	Cosmonaut regained control of spacecraft for entry attitude using manual control.
Soyuz 2	Soyuz 3 was unable to dock to the uncrewed Soyuz 2 spacecraft on orbit.	LOM	Soyuz 3 crew member misinterpreted orientation cues, repeatedly overrode the automatic docking system, and used nearly all his orientation fuel attempting to align and dock the spacecraft.
Soyuz 10	On orbit, the ionic sensors that were part of the automatic orientation system malfunctioned.	LOM	Commander manually took over control.
Soyuz 10	During Soyuz approach to Salyut in automatic mode the Soyuz oscillated from side to side.	LOM	At 150 meters the commander took over and manually soft docked to Salyut.

Soyuz 10	Post-docking, the crew was unable to release the capture latches to complete docking.	LOC	Crew was unable to release the capture latches, until ground called up a procedure to provide an electrical signal to release the capture latches as the signal was to be sent from Salyut.
Soyuz 11	After the docking problems that Soyuz 10 experienced, the Soyuz 11 crew used automated systems to maneuver within 100 meters of the Salyut then competed docking in manual mode.	LOM	The commander took over manual control at 100 meters to complete the docking to Salyut.
Soyuz 21	Igla automatic docking system failed during the last stage of rendezvous.	LOM	The crew of Soyuz 21 manually docked with the Salyut 5 station after a failure of the Igla automatic docking system at the last stage of rendezvous.
Soyuz 21	During preparation to return when the crew tried to undock, the docking latches failed to release properly. As the jets were fired to move the spacecraft away, the docking mechanism jammed, resulting in Soyuz being undocked, but still attached to Salyut.	LOC	The crew, using emergency procedures relayed from the ground, was able to finally disengage the latches.
Soyuz 33	Backup engine failed *on* during de-orbit burn.	LOC	Crew manually shut down engine and landed safely.
Soyuz T-2	Flight computer failure during rendezvous with Salyut 6.	LOM	Crew completed rendezvous and docking with Salyut 6 in manual mode.
Soyuz T-6	Soyuz spacecraft's automatic docking system failed.	LOM	Crew performed docking to Salyut 7 in manual mode.
Soyuz T-8	Radar antenna failure prevented automatic docking with Salyut 7.	LOM	Crew attempted to dock manually using optical sight and ground input, but was unsuccessful.
Soyuz T-13	Loss of power on Salyut 7 precluded automatic rendezvous and docking.	LOM	Crew performed manual docking to Salyut 7 due to loss of power on Salyut.
Soyuz T-15	Loss of power on Salyut 7 precluded automatic rendezvous and docking.	LOM	Crew performed manual docking to Salyut 7 due to loss of power on Salyut.
Soyuz TM-5	Kurs approach errors caused crew to disable automatic system.	LOM	Crew docked to Mir manually.

Soyuz TM-5	Crew error caused loss of auto control post undocking with Mir.	LOC	Crew regained control of spacecraft using manual control.
Soyuz TM-5	Soyuz orientation system failure prior to de-orbit burn.	LOC	Just before the scheduled deorbit burn, the Soyuz orientation system failed. When the engine did fire automatically, the commander shut it down. The crew made a second attempt to deorbit, but the automatic system shut it down and started a countdown to separate the propulsion module. The commander was able to stop the countdown and later performed a successful deorbit burn.
Soyuz TM-8	Kurs failure prevented automatic docking to Mir.	LOM	Crew docked to Mir manually.
Soyuz TM-17	Crew error caused loss of control and collision with Mir	LOC	Crew was able to regain control.
Soyuz TM-20	Soyuz computer failure prevented automatic docking.	LOM	Crew docked to Mir manually.
Soyuz TM-25	Kurs failure prevented automatic docking to Mir.	LOM	Crew docked to Mir manually.
Soyuz TM-26	Kurs failure prevented automatic docking to Mir.	LOM	Crew docked to Mir manually.
Soyuz TM-28	Kurs failure prevented automatic docking to Mir.	LOM	Crew docked to Mir manually.
Soyuz TM-30	Kurs failure prevented automatic docking to Mir.	LOM	Crew docked to Mir manually.
Soyuz TMA-5	Thruster 18 anomaly resulted in abort. Docking completed in manual mode.	LOM	Crew rendezvoused and docked to ISS manually.
Soyuz TMA-14	Automatic rendezvous / docking aborted due to software error. Crew completed docking in manual mode.	LOM	Crew rendezvoused and docked to ISS manually.
Progress M-24	Kurs anomalies during automatic approach resulted in a late abort (relative range of approximately 8 meters) and subsequent collision with Mir.	LOM	Crew docked Progress to Mir using TORU.

Progress M-33	For the first attempt of a long-range test of TORU, crew was unable to control the spacecraft due to inadequate TV view and unable to reduce the approach speed, so the docking was aborted.	LOM	Data necessary for a successful docking of the Progress was not displayed to the crew. Crew had not been previously trained for this approach and docking.
Progress M-34	For the second test of the TORU, the Kurs system was turned off, which prevented the commander from receiving the critical range and range rate data, and the Progress M-34 collided with the Mir Spektr Module (Mir EO-23).	LOC	Data necessary for a successful docking of the Progress was not displayed to the crew. Crew had not been previously trained for this approach and docking.
Progress M-35	Kurs aborted due to Mir computer problem.	LOM	Crew docked Progress to Mir using TORU.
Progress M-38	Kurs had fluctuations.	LOM	Crew docked Progress to Mir using TORU.
Progress M1-4	Kurs system failed.	LOM	Crew docked Progress to ISS using TORU.
Progress M-01M	Kurs had deviations in performance at 15 meters.	LOM	Crew docked Progress to ISS using TORU.
Progress M-53	Russian ground station failure resulted in inability to uplink commands to Progress to enable final automatic approach and docking.	Mission Delay	Crew docked Progress to ISS using TORU.
Progress M-58	The Kurs-A antenna failed to retract. The MCC-M commanded the antenna to retract and halted the automatic docking.	LOM	MCC-M instructed ISS crew to manually re-extend the Progress docking probe using TORU to increase clearance between ISS and Progress while troubleshooting the antenna issue. MCC-M subsequently retracted the probe in small increments. To complete docking and at the request of MCC-M, the crew manually closed the Service Module active hooks using the laptop computer, due to loss of command link with the Russian ground station.
Progress M-67	Progress in incorrect orientation at 12 meters.	LOM	Crew docked Progress to ISS using TORU.

Progress M-05M	Kurs failed one kilometer from ISS.	LOM	Crew docked Progress to ISS using TORU.
Progress M-08M	Kurs anomaly during station-keeping with ISS resulted in loss of automatic approach and docking capability (root cause later identified as ISS cable reconfiguration error).	LOM	Crew docked Progress to ISS using TORU.