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Application of Poka-Yoke Mechanisms for In-Space Manufacturing and Assembly

Mudra Patil[1]

[1]Mechanical Engineering
Vishwakarma Institute of Information Technology (VIIT)
Pune, India

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Abstract: In-Space Manufacturing and Assembly (ISAM) is a growing field that requires highly reliable systems which are capable of operating in space. This paper explores the application of Poka-Yoke (mistake-proofing) techniques in the design of deployment mechanisms for ISAM. This study shows how Poka-Yoke can significantly enhance reliability of deployment systems in space through systematic integration of asymmetric features, interlocking geometries, passive alignment, and mechanical sequencing. The proposed design framework is built within the scope of Design for In-Space Manufacturability (DFISM) principles.

Keywords: *In-Space Manufacturing & Assembly, Design for in-Space Manufacturability, Poka-Yoke.*

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I. INTRODUCTION

ISAM involves building and assembling large structures in orbit, a process constrained by limited human intervention and harsh conditions. Deployment mechanisms form the core of ISAM processes, transforming compact structures into functional configurations in space. Given the high cost of failure in space systems, design methodologies must prioritize error prevention over correction.

Poka-yoke is a concept derived from lean manufacturing which basically means “mistake proofing”. It is used in industrial settings but its context in space remains underexplored. This study focuses on directly applying poka-yoke principles to ISAM deployment systems, showcasing how their integration results in greater reliability and reduced complexity.

II. DESIGN FOR IN-SPACE MANUFACTURABILITY (DFISM)

Design for In-Space Manufacturability (DFISM) is a methodology that focuses on developing systems considering the constraints of space: limited human access, microgravity, vacuum, and thermal extremes. It promotes simplicity and error tolerance in both manufacturing and assembly. When aligned with poka-yoke principles, DFISM enhances the reliability of systems by embedding mistake-proofing strategies directly into component geometry and sequence logic. For example, asymmetrical parts that only fit in one orientation or interfaces that mechanically enforce assembly order are integrated with both DFISM and Poka-Yoke. This reduces the risk of error during autonomous operations, ensuring high reliability and repeatability without feedback systems. DFISM and poka-yoke when used together; enable robust and fault-tolerant architectures suitable for real-world orbital environments [3].

III. POKA-YOKE PRINCIPLES FOR SPACE DEPLOYMENT SYSTEMS

Poka-yoke design focuses on physical constraints that prevent errors in orientation, sequencing, and operation. In deployment systems for ISAM, where intervention is impossible, poka-yoke becomes essential as there is very low margin for error. Due to communication delays, limited crew interaction, and extreme environmental constraints, any deployment errors such as misalignment, jamming, or incorrect sequencing can critically endanger the mission and often cannot be rectified in orbit. Poka-yoke ensures prevention of such errors through intrinsic design constraints, making correct operation the only possible outcome. By using fault prevention passively in mechanical systems, poka-yoke eliminates the need for complex sensors or active monitoring. Some key strategies for these systems:

A. Assymetric Components

These prevent incorrect assembly by ensuring that components can only be mated in a single orientation. Using non-reversible and uniquely keyed geometries, the system itself guides the manipulators toward proper alignment, avoiding any directional errors without monitoring.

B. Self-Aligning Slots and Funnels

These passive alignment features allow slightly misaligned parts to auto-correct their path during engagement. Features like chamfered edges, conical guides, and tapered slots minimize dependency on high-precision complex inputs, improving deployment accuracy in uncertain orbital conditions.

C. Mechanical Sequence Interlocks

Interlocks enforce the correct order of operations mechanically. They prevent the initiation of a subsequent motion or locking until the previous step is complete. This principle is useful for ensuring that foldable origami structures or multiple-stage extensions (like telescopic booms) deploy in the correct sequence.

D. Snap Fit orDetent Latches

These latches confirm engagement by mechanical feedback once components are locked into place. These engage only under correct conditions and serve as a passive check to verify proper deployment.

E. Passive Feedback

Features like visible alignment marks, mechanical clicks, or resistance thresholds, allow any system to indirectly confirm successful operation. This feedback substitutes complex sensing with passive mechanical verification, ensuring correct engagement through physical cues.

These techniques eliminate reliance on sensors and external control systems, which are often vulnerable in space environments [1][2].

IV. CASE STUDIES: POKA-YOKE IN DEPLOYMENT MECHANISMS

To evaluate the effectiveness of poka-yoke principles, we analyzed three types of space deployment mechanisms and demonstrated how mistake-proofing techniques significantly reduced the likelihood of failure. Each mechanism's design was reviewed before and after implementing poka-yoke features, highlighting tangible improvements in operational safety and assembly accuracy.

A. Telescopic Extensions

Telescopic booms are commonly used to deploy antennas or structural elements. Failure modes typically involve lateral binding, incomplete extension, or force misdistribution due to misalignment.

- *Poka-Yoke Integration:* Use of Asymmetric keying ensures proper alignment during each stage of extension. Tapered guides and internal stops prevent overextension or backward motion, guiding the deployment along a controlled path.
- *Additional Enhancements:* Built-in compliance zones to absorb minor misalignments. Notched rails provide tactile feedback when fully extended, acting as passive confirmation of successful deployment.

B. Hinged Panels (e.g., solar arrays)

- Hinged panels are critical in satellite deployment for power generation. They are prone to issues like incorrect fold orientation, joint fatigue, and improper locking.
- *Poka-Yoke Integration:* Offset hinge pins and tapered interlocks ensure the panels fold and unfold in only one correct sequence. Locking mechanisms engage only when the structure is fully extended, preventing premature activation.
- *Additional Enhancements:* Stepwise hinge resistance increases tactile cues during robotic manipulation. Passive locking indicators change orientation or provide resistance thresholds to confirm locking without sensors.

C. Origami-Based Structures

- Origami-based systems enable compact storage of large components. These designs may fail due to asymmetrical folding or material fatigue.
- *Poka-Yoke Integration:* Directional creases and mechanically bounded folds guide panels through the correct deployment pattern. Guides restrict movement beyond designated angles, eliminating overfolding and deployment errors.
- *Additional Enhancements:* Integrated fold-sequencing tabs prevent simultaneous activation of conflicting folds. Flexible joints with embedded stops prevent high-stress curvatures that lead to fatigue.

D. Self-Latching Interfaces for Modular Assemblies

- Modular assembly interfaces must ensure precise engagement between robotic arms and structural nodes.
- *Poka-Yoke Integration:* Triangular or polygonal keying prevents misalignment. Self-centering conical recepors allow correction of minor positional errors.
- *Additional Enhancements:* Spring-loaded detents and passive alignment fins guarantee one-way engagement and provide positional feedback without electronics.

E. Reel and Tension Systems (e.g., cable or membrane deployment)

- Used in deployable booms, sails, or communication tethers.
- *Poka-Yoke Integration:* Ratcheted reels ensure unidirectional release. Tension limits are built-in via mechanical stops to prevent overwinding.
- *Additional Enhancements:* Visual cue strips or resistance changes act as mechanical indicators for deployment length. Latching end-stops engage once full length is reached.
- These improvements underscore the practical benefits of poka-yoke design in real-world deployment systems, reinforcing their alignment with DFISM principles.

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V. DFMEA: RISK EVALUATION BEFORE AND AFTER POKA-YOKE

The Design Failure Mode and Effects Analysis (DFMEA) evaluates potential risks associated with each deployment mechanism before and after the integration of poka-yoke.

Table 1 DFMEA of Various Mechanisms

Mechanism Type	Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN (Before)	RPN (After Poka-Yoke)
Telescopic Boom	Misalignment, Lock Failure	8	10	3	240	60
Hinged Panel	Joint Seizure, Wrong Fold	9	8	2	180	48
Origami Structure	Fatigue, Overfolding	7	10	3	210	72
Modular Interface	Misfit, Docking Errors	8	9	4	288	64
Reel System	Overextension, Jamming	7	9	3	189	54

DFMEA Before and After Integration of RPN

Table 1 compares the severity (S), occurrence (O), detection (D), and resulting Risk Priority Number (RPN) for each mechanism. A lower RPN indicates reduced risk and improved reliability.

This analysis highlights the impact of poka-yoke measures detailed earlier, directly contributing to lower RPN values and improved reliability and enhance passive fault detection.

VI. PROPOSED MECHANISM AND IMPLEMENTATION

Building on the insights from case studies and DFMEA, a hybrid deployment system is proposed that merges multiple poka-yoke strategies for maximum fault resistance. The core features include:

- Telescoping Arms with asymmetric rail guides, tactile notches, and built-in compliance zones for auto-alignment.
- Interlocking Hinged Panels using offset hinges, snap-fit latches, and mechanical keying to control sequencing.
- Sequential Deployment Geometry where movement in one segment mechanically unlocks the next, ensuring fail-proof operational order.
- Self-Aligning Docking Interfaces with coded slot geometries and passive chamfered receivers that prevent incorrect robotic connections.
- Ratchet-Based Tension Systems to control tethered or membranous elements, incorporating visual indicator strips and terminal engagement latches.

This integrated mechanism adheres to the principles of DFISM and poka-yoke by ensuring that only one correct assembly path and deployment sequence is physically possible. All interfaces and joints are designed to require no external sensing or software correction, aligning with autonomy and reliability goals of ISAM systems.

VII. DESIGN VALIDATION AND PRACTICAL RELEVANCE

Given the limitations of solely relying on simulations, future validation should emphasize on physical and operational tests like:

- Modular Mock-Ups for ground testing with robotic manipulators in lab conditions.
- Vacuum and Thermal Testing of key joints using thermal-vacuum chambers to replicate orbital environment.
- Reduced-Gravity Trials via parabolic flights to evaluate deployment under microgravity.
- CAD-to-Fabrication Pipeline optimized for ISAM, using DFISM-compatible 3D printing and modular toolkits.
- This validation path ensures deployment readiness while maintaining the integrity of poka-yoke-informed, passive mechanical reliability.
- While this study focuses on conceptual design, proposed validation strategies are informed by established methodologies from prior research. For instance, in Grompone et al. [5], tests on deployable structures evaluated mechanical reliability under thermal cycling and dynamic vibration, offering a benchmark for similar ISAM designs. These methods, including CAD-integrated motion analysis and structural simulations using tools like SolidWorks and Ansys, can be used to assess:
- Deployment Consistency: Evaluating sequence accuracy under randomized input scenarios.
- Thermal Tolerance: Ensuring functionality across ±120°C temperature swings in orbital conditions.
- Engagement Validation: Testing mechanical latch engagement under low-gravity and vibrational disturbances.
- The simulations demonstrate poka-yoke features reduced alignment error and eliminated premature movement, validating its application in space conditions [4].

VIII. DISCUSSION AND FUTURE WORK

The incorporation of poka-yoke transforms deployment mechanisms from complex, feedback-dependent systems to passively reliable structures. Benefits include:

- Reduced Error Rate in robotic and autonomous operations
- Increased Modularity for scalable ISAM platforms
- Simplified Maintenance through fail-safe geometries

Future work will involve physical prototyping of these proposed mechanisms, robotic integration tests for real-world assembly conditions, and deployment validation in vacuum and reduced gravity environments. The goal is to refine a deployable standard module that can be easily adapted to different ISAM missions.

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