The Concept of ‘Easily Serviceable Satellite’ and its Design Optimization

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Satellites are very complex systems and due to their knotty constructions, the servicer may not access the malfunctioning component without a long sequence of disassembly processes. One preferred method is to design and replace the components in modules for easy repairs. Having a universal design layout on satellite design would leverage an efficient maintenance service. However, since most satellites have unique designs which best suit their specific missions, the modularization of satellite systems haven't been widely adopted due to the lack of compatibility. This research aims to propose a design rule for the 'Easily serviceable satellite' in order to construct an assembly design guideline. Our goal is to optimize the configuration of satellite subsystems for easier service while maintaining their unique characteristics and requirements for their missions. These optimally rearranged subsystems can be either grouped or integrated to several service modules.

Key Words: Serviceable Satellite, Design for Assembly, Spatial Multi-Criteria Decision Making, System Reliability

Nomenclature

$d_{ServicePath}$	: Distance between a port and a target
d_{ToMove}	: Distance to move
$T_{Rem.Un}, T_{Rem.Snap}$	: Item removal time for unsecured/snap
$T_{Ins.Un}, T_{Ins.Snap}$	: Item insertion time for unsecured/snap
$T_{Acq}, T_{Setaside}$	: Item acquisition/set-aside time

Subscripts

$i, n, \text{ and } g$	: initial, intermediate, and goal state
t, o	: target and obstacle components

1. Introduction

In current satellite design, serviceability - the ease of maintenance - hasn't been much considered as a design rule. However, due to a considerable increase in needs for satellites, mass production of satellites would be required in the near future. Therefore, satellite designers should be able to assure that the initial design of the satellite is cost-effective, reliable and versatile enough for mass production. This research proposes to add the factor 'serviceability' to the design factor, which not only means the availability to replace parts for repair but also the quality measured by reliability standards. But, why would satellite designers have to pay attention to the serviceability? Here are some backgrounds¹⁾.

Responsive Space: A new paradigm which means "the capability of responding promptly to demands in space". This requires satellite systems with relatively short developing time and less cost. A pioneer of this concept is the TacSat of NASA, a modular spacecraft, which proposed a reliable system which can be manufactured and launched within several weeks.

On-orbit satellite servicing: A new space business model to send a servicer satellite along with the replacement component

modules to the target satellite system and get it fixed in space. Yet, this idea hasn't been widely applied, not due to the limitation of cutting-edge technologies but rather due to the lack of infrastructures to create a market. There is no drive to create a servicer network because the existing satellites (the client) were not designed for this type of service. On the other hand, if there is no solid working servicer to benefit from, satellite developers would not choose the design for service that degrade their optimal design for mission. To pull a trigger on this market, we would need an efficient satellite design which is easily serviceable yet least sacrifice the optimality of each mission specific satellite.

There have been many related works for optimal layout of satellite components so far. The past work²⁾ by Sun and Teng (2003) showed effective solution strategy for the optimal layout using traveling salesman problem model-based ant colony optimization algorithm. But, what has been less considered in the past researches is the design factors for the on-orbit servicing. Unlike ground-based repair, space-based repairs have few opportunities for human labor. This Easily Serviceable design for on-orbit servicing needs to be more focused on the accessible route with the fewest obstacles for robotic manipulation.

Design for Easily Serviceable Satellites also starts from reconfiguring the current layout as most other modularization processes commonly do. The satellite layout problem hasn't been considered seriously except for some perceived spatial constraints, such as thermal conditions and clear field of view for sensors. This means that reconfiguration is eligible for a parameter with a high degree of freedom in design optimization. Therefore, reconfiguration may be the important factor in the satellite design if the modularization matters to the satellite systems.

2. Problem Definition

The satellite layout reconfiguration intends to improve the service efficiency and optimize the assembly sequence but avoid spatial misalignment of components. This problem was analyzed based on the following viewpoints.

*Design for assembly*³⁾: Let us suppose that there is a high-failure component located in the hard-to-access zone of a satellite. If the component breaks down, developers have to repeat the disassembly and reassembly sequences to get it fixed. This work process will get longer as the conventional satellite is made of a large number of complex subsystems. Fig. 1 describes a notional liaison diagram⁴⁾ of a satellite.

Fig. 1. Notional liaison diagram of Nano-JASMINE satellite developed by the University of Tokyo.

Such complex liaison of a satellite means that disassembly and reassembly process would be a serious task in case of the mass production or on-orbit servicing. If optimal layout for servicing is applied to the satellite design in the early stage, we can anticipate the benefits given below:

- Reducing levels of assembly
- Providing easy access to malfunctioning components
- Optimizing manufacturing processes
- Improving product reliability

Spatial Multi-Criteria Decision Making (MCDM): This technique is commonly used in solving land use problems with Geographic Information Systems (GIS) for urban planning. Its final decision, namely the spatial rearrangement of alternative, is determined by spatial variability defined geologically. Easily Serviceable Satellite Design can be also conceptualized as a spatial MCDM problem with spatial sensitivities. And the final decision would be the appropriate or optimal configuration of the components.

3. Quantification of the Qualitative Criteria

The criteria that this research deals with are uncertain and incomplete descriptions. To solve the decision problem with the criteria, qualitative approaches are required. For example, the Analytic Hierarchy Process for dealing with complex decisions involves quality ranking, prioritization and pair-wise comparisons.

3.1. Definitions of criteria

In general, a component's serviceability increases if the component is installed on the panel, otherwise decreases when placed on the platform. But in practice, even though the component is installed on the platform the component's serviceability would be higher compared to the one installed on the panel far from the port if the servicing route between the component and the servicing port (i.e., a hinged door or a removable panel) is short and has a few obstacles. Therefore, this research proposes a definition of the cost of serviceability as follows:

$$\text{Serviceability} = \text{Accessibility} + \text{Modularity} \quad (1)$$

Fig. 2. Description of accessibility.

$$\text{Accessibility}_i = LoE_i + d_{\text{ServicePath}} + \sum_o^{N_{\text{obstacle}}} (LoE_o + LoM_o) \quad (2)$$

Accessibility: How easy the servicer's manipulator can approach the targets in the system (Fig. 2). If there are more obstacles on the servicing route from the servicing port to the target, accessibility would get worse. In order to access the target, obstacle must move in the direction described as 'Direction to Move' in Fig. 2. This paper proposes to define *accessibility* as the combination of several factors; *LoE* and *LoM* of each obstacle, path distance from the port for servicing.

Level of Effort (LoE): a criterion related to the design for assembly, the amount of work determined by the number of disassembly and the reassembly sequence, the difficulties in calibration and the *Time to Service* for providing access to other parts that should be serviced

Time to Service (TTS): According to the DFA methodology (Dewhurst, 1990), ideal service time can be given by:

$$TTS = \frac{2 \times T_{\text{Rem.Un}} + T_{\text{Rem.Snap}}}{3} + \frac{2 \times T_{\text{Ins.Un}} + T_{\text{Ins.Snap}}}{3} + T_{\text{Acq}} + T_{\text{Setaside}} \quad (3)$$

Level of Movability (LoM): A combination of the *Distance to move* and the *Degree of Mobility (DoM)* which determines how easily the component can move its position to be serviced or to provide access to the others.

$$\text{Level of Movability} = DoM + d_{\text{ToMove}} \quad (4)$$

Servicing Path Distance: The distance in the system between the servicing port and the target

Modularity: The ability to build a module by combining coupled components

$$\text{Modularity} = \text{DoI} + \text{Storability} + \text{Connectivity} \quad (5)$$

Degree of Interdependence (DoI): How close components mutually interconnected with other components.

Storability: A criterion for evaluating the space utilization, which is the percentage of volume for grouped subsystems in a module frame

Connectivity: A criterion in order to reduce complex wires and harnesses between the interconnected components. This may relate to the total length and the number of crossing of all wiring.

Before starting multi-criteria decision making, designers should compare the criteria pair-wise and decide which is more important and to what extent. Priorities are calculated based on the judgment as relative score on a scale.

In this research, the criterion *accessibility* has a high priority, and *connectivity*, *modularity* are relatively low priority. And in case of attribute factors as well as criteria, each of the factors is given a weighting and a rank (Table 1).

4. Spatial Analysis for Satellite Systems

All satellite’s components, bus systems and payloads will be installed on the area consist of panels, platforms or decks. Yet these areas have spatial features as follows:

- Easy to balance : near the center of gravity
- Vibration/Shock/Contamination-sensitive
- Clear field of view for sensors
- Thermally stable/unstable : heating source and sink

Most spatial features are fixed, but some can be changed by the installed components, such as the vibration induced by the perturbation of a reaction wheel. Each of the components should be sited in appropriate or feasible regions considering its spatial features and physical limits. In this section, we describe the satellite model for spatial MCDM and introduce an implementation ‘IMESS (Intelligent Modeler for Easily Serviceable Satellite)’ using Visual Studio C++.

4.1. Spatial multi-criteria decision rules

This spatial MCDM decision problem must satisfy not only the criteria mentioned previously, but also the general rules⁵⁾ given below:

- Locate the most constrained component first.
- Locate massive components near the launch vehicle interface.
- Make mass distribution as symmetrical.
- Put propellant tanks near the system’s center of gravity.

Then, the objectives for the easily serviceable satellite can be summarized as follows:

- Maximize: serviceability, accessibility, simplicity (wiring), space utilization, and stiffness
- Minimize change to the existing system: the position of the center of gravity / the moment of inertia of the whole body
- Minimize, Reduce:
 - Servicing route distance from the servicer manipulator
 - The number of disassembly / reassembly sequences
 - Trade-off: additional cost for standardizing systems

- Find the best:

- Size of servicing port to enable to cover all servicing area.
- Thermal profile for heat transfer; Separate heating sources into different groups/modules. In the current design process, heat transfer is the most important consideration.

Consequently, spatial MCDM aims to search desirable locations providing stiffness, positional stability and protection from structural loads and vibrations to provide access to install or repair components.

4.2. Decision factors: constraints handling

Constraints handling can adjust the interaction between criteria and reduce the search space. Since this decision problem deals with many conflicting criteria and the decision makers’ preferences vary depending on their missions, the constraints handling is important to an effective decision making. In this decision problem, some constraints are defined by the decision makers, namely satellite designers. They may specify their preference in the user’s input list (Table 1). This list is used by IMESS and includes following information:

- Weightings on grid cells of panels and platforms
- Components’ physical properties and spatial sensitivities
- Interconnected components and their wiring complexity

This list is designed to identify which components have priority to rearrange layout, and it is worthy as a knowledge database for the space infrastructure⁶⁾.

Table 1. The user’s input list.

CURRENT SYSTEM ANALYSIS		CHARACTERISTICS PARAMETERS				SPATIAL CONSTRAINTS							
SUBSYSTEM	COMPONENTS	Serviceable	Movable	Weight H/M/L	SIZE L/M/S	HEAT source /sink	Heat	Sun light	Sensitive To Contamination	Clear FoV	Vibration	PANEL	DECK
Mission Payload	Telescope	o (Hard)	x	H	L	source	o	o	o	o	o	o	o
	Optical Bench	x	x	H	L	source	o	o	o	o	o	o	o
	Reaction Wheel	o (Hard)	x	L	S						Cause		o
	CMG	o	o	L	M								
	Magnetic Torquer	o	o	M	M								
	Magnetic Cancellor	o	o	L	M								
	Magnetometer	o	o	L	S								
Attitude Control	Earth Sensor	o	o	L	M			o	o	o	o	o	x
	Sun Sensor	o	o	L	S			o	o	o	o	o	x
	Star Tracker	o	x	M	M			o	o	o	o	o	x
	Gyroscope	o	o	M	M			o	o	o	o	o	x
	Motion Reference Unit	o	o	L	S								
	Inertial Reference Unit	o	o	L	S								
	Thermal Sensor	o	o	L	S								
Command & Data	OBG (CPU)	o	o	L	M	source	o			o			x
	OBG (Mem & HDD)	o	o	L	S					o			x
	Transmitter	o	o	L	S								
Communication	Receiver	o	o	L	S								
	Duplexer	o	o	L	S								
	Antenna	o	x	L	S					o		o	x
	GPS	o	o	L	S					o			
Power	Battery	o	o	H	M	source	o	o	o	o			x
	Solar Cell	x	x	M	L						o		
	Power Control Unit	o	o	L	S								
Propulsion	Thruster	o	o	M	M	source				Cause		Cause	o
	Propellant Tank	o (Hard)	x	H	L					o			o
Thermal Control	Radiator	x	x	M	M	sink							
	Heat Pipe	x	x	M	M	sink							

CURRENT SYSTEM ANALYSIS		RELATIONSHIP				ASSEMBLY OPERATIONS							
SUBSYSTEM	COMPONENTS	Functional Attributes	Measure	Relationship	Follow-up	Type	No. of Connectors	Mating component	Type	No. of Connectors	Mating component	Type	No. of Connectors
Mission Payload	Telescope	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Optical Bench	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Reaction Wheel	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	CMG	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Magnetic Torquer	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Magnetic Cancellor	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Magnetometer	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Attitude Control	Earth Sensor	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Sun Sensor	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Star Tracker	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Gyroscope	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Motion Reference Unit	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Inertial Reference Unit	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Thermal Sensor	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Command & Data	OBG (CPU)	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	OBG (Mem & HDD)	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Transmitter	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Communication	Receiver	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Duplexer	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Antenna	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	GPS	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Power	Battery	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Solar Cell	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Power Control Unit	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Propulsion	Thruster	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Propellant Tank	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
Thermal Control	Radiator	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3
	Heat Pipe	Measure	Tele-housing	Follow-up	CPU	Wiring	1	CPU	Fasten	3	Deck	Fasten	3

The decision makers can customize their systems by choosing the components for their mission in this list, which are classified into categories depending on their sensitivity and serviceability as described in Fig. 3.

Components with weak spatial constraints, for example, the insensitive and the unserviceable, have a high degree of freedom and so their priorities should be set to low.

Fig. 3. Categorization of constraints.

4.3. Raster model as the configuration space

To analyze the spatial problem, we construct the configuration space of the satellite system using raster data model which is commonly used in GIS. The raster model consists an array of identical square cells by a row and column number and contains a number representing the type or value of the attribute. The data in each cell means the inherent characteristics of a region. For example, the region with weighting 2 means that area contains components which may cause high shock. A well-constructed raster model can be used to represent continuous spatial features of the satellite body.

Fig. 4. A raster model for Nano-JASMINE.

IMESS use 20×20×20 raster cubes as default to describe a cube-type body.

4.4. Reconfiguration procedure

In this section, we start to identify optimal configuration for the Easily Serviceable satellite system. The demonstration of reconfiguration using IMESS is placing thirty-four components on the 20×20×20 raster cubes so that they can have maximum serviceability. Each step of the process proceeds as follows:

STEP 1. Split the area into regions depending on the spatial sensitivity. These regions can be adjacent or can be overlapped with others. The components must be placed within the feasible region selected by the designer in the user's input list. Thus, the solution requires that no components share the same position and place out of the feasible region. Every component has its own available region

to be placed, which is called 'Region[A]' of component A. Also, a certain parcel of a panel is to be a port accessible from the servicer (or the developer). Assume that the characteristics of the region have been determined using developers' empirical data on the user's input list. Generally, Region[X] on the panel side has good accessibility from the port.

STEP 2. Set the initial position of each component roughly in the following procedure:

1. Locate first the immovable components.
2. Locate movable and sensitive components roughly.
3. Locate insensitive & serviceable components on the panel providing access for servicing roughly.
4. Locate unserviceable components on the platform roughly.

However, we can assume that the initial configuration is reasonably optimal for the system itself. Hence, it doesn't matter whether the search starts with all components on their default positions of the current system.

STEP 3. Determine all the shortest routes from servicing ports with fewer obstacles in the sequence of Fig. 5. This is equivalent to the maximize coverage of servicing from the servicing port. Identify optimal location of the component to maximize accessibility⁷⁾.

Fig. 5. The flowchart of the STEP 3 process.

After locating the first component with the highest priority, it calculates the distance from the port and counts the number of obstacles, then determines the immediate position where the number of obstacles is smallest using a heuristic. The problem can be quite computationally heavy as there are many possible configurations of components, and may be hard to find feasible solutions. In order to reduce exhausted search and space complexity, adaptive A* algorithm is applied. The A* algorithm finds the shortest distance plus least cost path from an initial state to possible goal states via immediate state. Let N_{obstacle} be the number of the obstacles against the service target, operator (n) is the set of positions with N_{obstacle} -th elements. The elements of operator (n) are ordered according

to lowest LoE first. Then $h(n)$ is the sum of the costs of the elements in operator (n) . If the current state does not meet the constraints, search node will continue to the next state (n) .

Fig. 6. A solution tree using adaptive A* search.

A trace of searching is shown in Fig. 6. At the initial state, N_{obstacle} -th feasible states that can be generated, then $h(n)$ is calculated for these newly generated states. $f(n)$ is calculated by summing $g(n)$ and $h(n)$. The state with the lowest $f(n)$ value among all the active states is selected as the next state for further expansion. As a result, we can find the possible combinations the positions of thirty-four components (Fig. 7), reducing the number of obstacles and improving the accessibility of serviceable components (Table 2).

Fig. 7. Servicing routes preferred optimization: before and after.

Table 2. Results on the number of obstacles and accessibility.

Serviceable Components	Before		After	
	N. Obst	Accessibility	N. Obst	Accessibility
Magnetometer	7	103.24	0	11.5
	6	88.23	3	46.39
	6	96.16	2	30.88
Transmitter	6	138.31	0	7.65
Receiver	5	115.32	0	7.9
Duplexer	3	37.66	0	8.4
Battery	4	61.76	0	8.5
	4	53.88	0	9.7
Total	41	694.56	5	130.92

STEP 4. Determine all the shortest path alternatives for each pair of connected components. Identify the shortest path that connects a specified set of points. Cable mass which is involved in the criterion ‘Connectivity’ can be reduced by co-locating components with many interconnections, namely CPU. This step provides the access for installing wiring and connectors and rooms for the necessary bends of cables.

STEP 5. Compare the position of the center of gravity and check the spatial feasibility if there is no position overlapping of the components. But in practice, we need more criteria to judge whether this result is rational to real systems.

5. System Analysis of the Easily Serviceable Satellite

To analyze a system from viewpoints of the serviceability, we will examine the previous result by the serviceability block diagram modifying a reliability block diagram⁸⁾. In practice, an easily serviceable configuration is equivalent to arranging components in parallel. Hence we can expect that the effect will improve reliability by converting series configuration to parallel.

The reliability block diagram consists of a series of blocks connected in parallel or series configuration. Consider a system with n -component, and if we assume $M_x(t)$ the event ‘component x is operating at time t ’, the reliability $R(t)$ of the system can be written in the form⁸⁾ in case of:

Series configuration

$$R(t) = P(M_1(t) \cap M_2(t) \cap \dots \cap M_n(t)) \quad (6)$$

Parallel configuration

$$R(t) = P(M_1(t) \cup M_2(t) \cup \dots \cup M_n(t)) \quad (7)$$

where $P(B)$ is denoted by total probability theorem,

$$P(B) = \sum_x P(B/A_x)P(A_x) \quad (8)$$

Adopting the notations used in the reliability block diagram, we can have the serviceability block diagram as Fig. 8. A servicer starts to disassemble from the point ‘IN’, then reaching the point ‘OUT’, it turn back to the ‘IN’ as reassembling. Converting the meaning of $M_x(t)$ of Eq. (6) and (7) to the ‘ability to service component x ’, we can understand the effect of reconfiguration from the viewpoint of reliability.

Fig. 8. Serviceability-block diagrams, before and after reconfiguration.

6. Conclusions and Future Work

The main contribution of the proposed concept ‘Easily Serviceable Satellite Design’ is its ability to address the spatial misalignment from the viewpoint of servicing and provide criteria for a reliable and robust design. Moreover, this research can be extended to the following works.

*On-Orbit Serviceable Satellite Design*⁹⁾: Consider a further range of servicing on-orbit instead of ground-based. Setting parameters for on-orbit servicing is more complex than ground-based due to the space environment where satellites operate. We should take into account the additional parameters for on-orbit servicing, such as automated assembly, calibration and a manipulator to perform the job.

Modularization: Modularization can be characterized as a partitioning system into functionally independent parts. To partition a whole system, it is necessary to reconfigure layout considering the spatial features and the interconnection between components. The state-of-the-art of a modular satellite design is focusing on the module with the standardized interface such as space plug-and-play avionics. The approach of this research which focuses on the contents of the module instead of the interface will provide another viewpoint to the modularization.

Device-Driven Automatic Geometry Creation: Satellite designers try to make systems with a lighter weight and volume, also which is easy to design, and manufacture. But it is very hard to conceptualize a creative model that they never have imagined. This research will induce a creative shape of easily-serviceable satellites which will differ from the general shape of the satellite, such as a cube or a hexagonal prism. Most current satellite shapes have multiple plates to install the components or to shield their body. But these common shapes may not best suit their missions and spatial environments. We expect that there may be other perfect-fitted shape that may have a better balance. So in the future work, I would like to propose a model generation rule in order to search for a creative satellite frame using meta-heuristic. The fundamental scenario of the model generation is given below:

1. Imagine several planes adjacent to the each group of components.
2. Analyze the spatial relationships between planes by planar contact mechanics.
3. Create a volume by mating planes.

In practice, however, creating mating features is an extensive work because the model deals with a high degree of freedom and uncertain and incomplete geometry factors. Further research may be needed to adjust the key geometry factors in order to simplify the model and keep the simulation load to an appropriate level.

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