Enabling Technologies for Microspacecraft

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Abstract— Microspacecraft (under 100 kg dry mass) have the potential to provide significant advances over current state-of-the-art, spacecraft, and mission designs by providing a revolutionary concept that leads to potential new paradigms for space applications. A modular design approach is required to meet the stringent cost goals. Modularity and standard interfaces provide inherent multi-mission capability by allowing the user to tailor the spacecraft to a variety of configurations: a communications platform, science platform, or potentially a science payload delivery system. This modular building-block approach allows cost-effective use of individual "expendable" micro-spacecraft for single use missions such as on-orbit servicing or rapid response satellite inspection. The microspacecraft can also be used as an integral part of a distributed satellite system (DSS) to provide revolutionary capability to essentially reconfigure on-orbit a "virtual" spacecraft mission to account for changing mission priorities and degradation or loss of DSS elements either due to natural or induced environments[1].

Dozens of constellation missions have been proposed at the AIAA/Utah State Small Spacecraft Conference using spacecraft as small as 10 kg. Proper design of constellations that feature graceful degradation permits simplifications in individual spacecraft such as single string components. The microspacecraft provides enabling capability, which cuts across commercial, defense and science missions.

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1. INTRODUCTION

Lockheed Martin Astronautics (LMA) has been involved in development of planetary spacecraft since the Viking Lander in 1971. Planetary spacecraft have traditionally driven the need for lighter weight, lower power and lower volume spacecraft to support the stringent interplanetary launch energy, or delta velocity requirements. Planetary spacecraft, such as the Mars Observer (MO) launched in the early 1990s, had a propellant-loaded (i.e., wet) mass on the order of 2000 kilograms (kg). The MO mass was driven by the use of about 14 large electronics black boxes. As a result, it required the throw weight and cost of the Titan *III*, the nations largest operational expendable launch vehicle at that time. Due to NASA's funding constraints, the 1990s brought a new vision to significantly reduce mission costs by flying on a more frequent basis, with a more limited science mission.

This new paradigm has been denoted as "Faster, Better, Cheaper" (FBC). The "Faster, Better, Cheaper" Mars Global Surveyor (MGS) replacement for the failed Mars Observer, was designed and developed by LMA for NASA's Mars Surveyor Program under the direction of the Jet Propulsion Laboratory (JPL). The paradigm shift, graphically depicted in Figure 1, shows the significant reduction in spacecraft wet mass as a function of missions.

It also important to note that this reduction in mass correlates with a significant reduction in spacecraft and mission cost. For the ~$1B cost of the Galileo mission, the NASA FBC approach has fielded 11 missions. While not all of the 28 individual missions have been completely successful, there have been significant scientific and technical accomplishments over a much broader range of missions. MGS, developed in only 27 months, was launched in 1996 and completed the final stages of aerobraking in March 1999, into the Mars science-acquisition phase. MGS had a launch, wet mass on the order of 1100 kg; nearly half the mass of the original Mars Observer. This required significant technical innovations to reduce mass, including the first ever use of an all-composite planetary spacecraft bus and at a significantly reduced cost. Expanding on the "Faster, Better, Cheaper" paradigm, the Mars Surveyor launch masses for orbiters and landers in 1998 and 2001 are under 600 kg, thus representing another factor of two reduction. The reduced mass of the spacecraft resulted in a nearly a 2X reduction in program cost compared to MO, due in part to a lower spacecraft cost and reduced science payload, but also its ability to launch on a smaller launch vehicle.

[1]

These mass savings were only attainable through significant technology investments: low-power and low-mass avionics, composite structures incorporating the latest advancements in materials and design processes, and implementing innovative mission design concepts such as aerobraking to reduce the on-board propellant requirements. These same investments and resulting innovations have also been leveraged by LMA to develop "Faster, Better, Cheaper" spacecraft for the NASA Discovery Program.

Lockheed Martin Astronautics is currently supporting the mission operations phase of Stardust, a spacecraft that will perform a fly-by of the comet Wild-2 at a distance of 60 miles from the comet nucleus and, capture and return cometary dust to Earth for analyses in 2006. LMA is designing and developing several more NASA spacecraft, including the Mars Surveyor '01 Orbiter and Lander, Mars Surveyor '03/'05 Lander and Genesis, another NASA Discovery mission.

The technical challenge of providing microspacecraft in the *20 kg* to 100 kg dry mass, represents another 3X to 10X reduction in mass, requires another major evolution and possibly revolution of today's approaches, not only to the spacecraft design but also to the mission design. Strategic investments are required in developing highly capable miniaturized spacecraft components and subsystems.

2. MICROSPACECRAFT CONCEPTS

Several microspacecraft concepts and space system architectures have recently been proposed which provide revolutionary approaches to future space system architectures. These include the Mars Micromission Spacecraft (MMSC) Bus concept, proposed by JPL, which offers another opportunity and challenge to develop a low-cost approach to accomplish important probe deliveries, network science and orbital investigations, as well as establishing a Mars infrastructure for enhancing communications and navigation. LMA studies have concluded that these missions, planned for launch in 2002, 2005 and 2007 as a secondary payload on an Ariane 5, are feasible, and that there is a low-cost approach to developing the common carrier bus for all mission types [1]. The team has developed a baseline common carrier that satisfies the 2002 mission requirements with a high level of heritage from our ongoing Mars and Discovery missions. The Air Force Research Laboratory (AFRL) has developed a distributed aperture synthetic aperture radar (SAR)/moving target indication (MTI) capability which utilizes collaborative clusters of highly capable ~100kg microspacecraft. The New Millennium Program has recently selected a micro/nanospacecraft constellation for the Space Technology 5 (ST5) mission to demonstrate collaborative

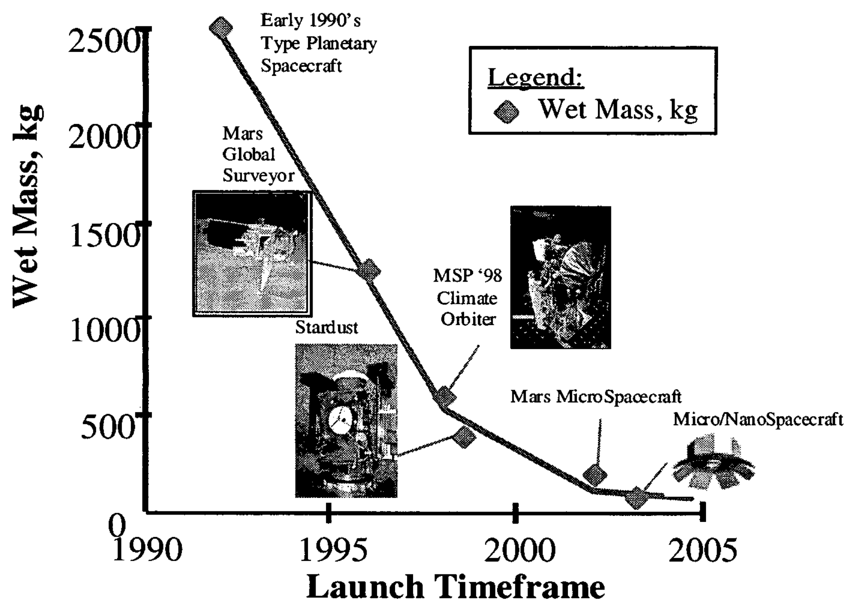

Figure 1 Evolution of Spacecraft Mass

constellation science. Each of these missions takes advantage of a number of new technologies that are already in development with internal funds or other commercial and government programs such as the Air Force Research Laboratory (AFRL) sponsored Advanced Technology Demonstration Spacecraft (ATDS) development of multifunctional structures (MFS) in conjunction with LMA investment in this technology area.

3. ENABLING TECHNOLOGIES

The low dry mass of these microspacecraft concepts, ranging from the low tens of kilograms to 70 kg, is indicative of enabling technologies required for each of the spacecraft's subsystems. The technologies are also directly applicable to future upgrades of today's current earth orbiting spacecraft missions. Studies have shown the mass of the existing Global Positioning Systems (GPS) spacecraft could be reduced by a factor of nearly 2 with implementation of these same technologies, which enable a microspacecraft. The remainder of this paper discusses specific enabling technologies for the mission and selected subsystems of the spacecraft: propulsion, command and data handling/electrical power system (C&DH/EPS), structures, cabling, guidance/navigation/control (GN&C) and aeroassist. The majority of the mass reductions achieved recently in Mars missions has been due to the use of aerobraking. Further major advances are possible with major reductions coming in electronics and MFS.

Propulsion

High specific impulse propulsion is required to reduce the propellant mass. Major advances are being made in propulsion for small spacecraft with smaller bipropellant engines (R6C), dual mode engines (SCAT), lightweight composite tanks (JPL), and smaller pressurization systems. Recent JPL technology investments have resulted in a factor of 2 reduction in propulsion system mass. MGS achieved major mass reductions by using a dual mode propulsion system instead of the MO bipropellant that required a separate monopropellant system. The NASA New Millennium Deep Space 1 (DS1) has successfully demonstrated the use of Xenon Ion propulsion for interplanetary spacecraft missions. The large size of ion engines and high power consumption has precluded their use on microspacecraft missions. However, advances in this area to reduce power consumption from kilowatts to 150 w are in work. Hybrid propulsion is being pursued by several agencies due to the reduction in tank mass and pressurization system mass.

LMA heritage in high specific impulse bipropellant propulsion design started with the Cassini mission. The decision between bipropellant and dual mode mainly hinges on the engine cost and development schedule. Primex and JPL have developed a modified hydrazine thruster with an ultrafast Wright valve in development, providing low minimum impulse bit (MIB), that is ideal for attitude control for these long missions. Use of this thruster and the dual mode system reduces launch mass by over 5 kg and eliminates the extra cost of reaction wheels and provides more payload volume and mass. New propulsion technologies, which offer higher specific impulse and additional mass savings, include micro-hydrazine thrusters, MEMS subliming single-shot thrusters, microPPT, and MEMS reaction wheels.

Command &Data Handling (C&DH)/Electrical Power System (EPS)

The mass and power consumption of the electronics has driven spacecraft size due to a large number of black boxes, cabling, and the need for large batteries. Advances in integrated electronics and packaging techniques offer major mass reduction for future small spacecraft. It is now possible to place most of the C&DH and EPS functions for small spacecraft on a single module. Processors now in development such as the G4 will allow much more on-board capability for autonomous operation, data correlation, and data compression.

High Density Interconnect (HDI) packaging of circuits provides approximately twice the functional capability of a typical VME circuit card assembly in less than 20% of the area and 40% of the weight. HDI packaging combined with Extreme Density Packaging (EDP) can reduce a typical electronics box footprint from 8 x 9.5 in.^{2} to 3.3 x 6.6 in.^{2} or a volume reduction from 606 in.^{3} to 90 in.^{3} ~84%. Similarly, EDP can reduce a typical box mass from 25 kg to 5 kg, an ~80% reduction. The LMA process supports repairability and line replaceability. An additional benefit from this technology is improved environmental, mechanical, and thermal performance. The functions of the C&DH and EPS can be combined in a single box to further reduce the overall subsystem mass.

HDI is an advanced circuit packaging technology to reduce volume and weight while improving capability. Each HDI module is a 3-D ceramic circuit block substrate, bonded semiconductor die and HDI submodules, laminated layers of Kapton and metal, interconnections between layers made by laser-drilling and sputter-filled vias, and SMT components attached on top of the lamination. Thus, the HDI modules provide "caseless" circuitry.

Multifunctional Structures

Many advances are being made in the use of multifunctional structures to reduce cabling mass, radiator mass, and to provide large aperture devices for small spacecraft. Integration of solar arrays with structural panels that can act as aerobrakes is one example of MFS. Another approach is to combine solar arrays with energy storage (small lithium batteries) and power distribution on a single panel.

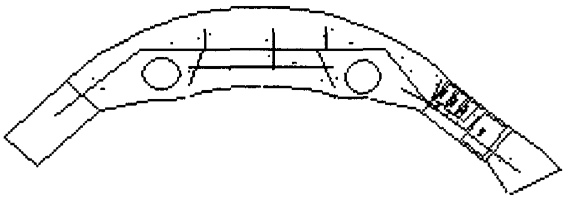

Figure 2 "Flex Circuit " Layout on MMSC Forward Equipment Deck

As noted earlier, the use of an all-composite structure meets or surpasses all the factors of safety required for launch and at MEOP and significantly reduces the dry mass. LMA has been developing multifunctional structures (MFS) which integrate the C&DH/EPS electronics, thermal control, and power and data distribution into a structural panel. These "flex circuit designs" are sized to each conductor for a specified voltage drop as a function of current and the length of the run. Our design uses Flex-to-Flex connections to avoid the use of two-piece connectors. This design includes spare traces/rework vias to support modifications and repair as needed. Figure 2 depicts a design for the MMSC Forward Equipment Deck. Options to the "flex circuit designs" include shields, coatings and ground planes and they could also be added as required. The flex approach has enabled us to replace traditional cabling, typically on the order or 5-10kg with a much simpler, more manufacturable flex circuit design of only 1kg. The MFS concept lends itself particularly well to inflatable structures concepts, which enable very large deployed apertures or solar sail concepts.

Aeroassist

Aeroassist techniques for planetary missions have been developed in recent years for aerobraking, aerocapture, and precision landing. The MSR mission will employ aerocapture and aerobraking for the French orbiter to reduce the launch mass and allow an Ariane 5 to launch both an orbiter and a lander simultaneously.

The 2003 lander will aeromaneuver to reduce the size of the lander footprint (the error ellipse). Aerobraking at Mars for the science and telecom orbiters to achieve circular orbit saves tens of kg in propellant mass. LMA has relied on our past experience with aerobraking design, manufacture and operations for Magellan and MGS in assessing the aerobraking phase of the mission. This approach was used very effectively in the aerobrake design of MGS using two very simple Kapton and fiberglass panels. For MGS, the flaps were passively deployed after launch and weighed less than a half a kilogram apiece. The MMSC spacecraft has an unusual shape for aerobraking, so one of our first steps was to look into its aerodynamic stability. This assessment used state of the art free molecular aerodynamics and direct simulation Monte Carlo (DSMC) codes. The initial study concluded that the basic shape with cg per Ariane constraints is unstable about its long axis.

Ballast mass required to shift the cg to a stable location for aerobraking is prohibitive so the addition of drag flaps was investigated. This approach creates a stable configuration by shifting the center of pressure behind the center of mass of the vehicle. Packaging studies concluded two rectangular pop-out flaps 0.9 by 0.6 m could be attached to the back of the vehicle. The two MGS panels were added fairly late in the design process when design margins for atmospheric uncertainties doubled.

Our flap trade concluded that a 75-degree flap angle would produce good stability for the satellite while also maximizing drag efficiency by increasing the projected area of the vehicle by 50%. Use of DSMC techniques also generates heating distribution information for thermal analyses. Examples of the Free Molecular Aerodynamics Models are shown in Figure 3. After assessing the thermal balance of the flight system, we conclude that the basic freestream heating rate for aerobraking can be increased to about 0.34 W/cm2 with a 100% margin for atmospheric instability.

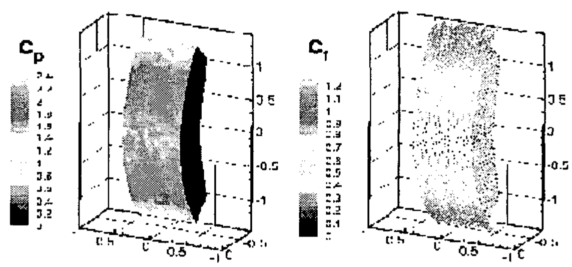

Figure 3 Free Molecular Aerodynamics Model

Power Collection and Storage

Advances in solar cell efficiency and battery energy density will greatly reduce spacecraft mass. Lithium ion and lithium polymer battery technology is in test for the 2001 Mars lander to replace bulky Nickel Hydrogen batteries.

The future use of lightweight solar arrays based upon thin film photovoltaics on flexible substrates offers the potential to provide specific powers of over 100-200 Watts/kg (W/kg) compared to traditional rigid cells on either rigid or flexible substrates ranging from 25-66 W/kg, respectively. These lightweight solar arrays are amenable to multifunctional packaging and deployment with inflatable structures, which can also act as antennas, drag flaps, or structural members while providing power generation and distribution. Low cost thin film photovoltaics are derived from the large area techniques used to manufacture the semiconductor material. These large area techniques offer the potential $10-50$/W compared to the specific cost of Si at 100-250$/W and GaAs derivatives at 400-1000$/W.

Guidance, Navigation, and Control

Major advances in Guidance, Navigation, and Control are close to reality. Much smaller IMU's, star cameras, reaction wheels, and on-board processing for autonomous navigation are available. Litton has developed small IFOG's for microspacecraft but Draper Labs is working on a third generation MEMS IMU that has a mass of less than 50 grams, including a processor. This processor may even serve as the main spacecraft computer. Clementine and Mars Surveyor used a one-kg, wide-angle star camera from OCA. AFRL is working on small MEMS star cameras that will have a mass of 100 grams or less and hundreds of steerable mirrors. On-board navigation as demonstrated by DS-1 will reduce the cost of ground based radio navigation that is not effective and drives spacecraft power.

with drag flaps are only some of the technologies required to reduce dry mass further.

Multifunctional structures can be taken to higher levels of integration, which integrate the structural and electronics functions of a spacecraft to further reduce mass and associated assembly and test costs. Table 1 illustrates an example mass allocation for a future Mars Microspacecraft. It includes some enabling technologies that were discussed earlier. There are advances in power subsystems, including lightweight solar arrays and lithium batteries. Alternative approaches to traditional computing, such as optically based processors that can provide multiple functions in a single component, i.e., integrate guidance, tracking, rendezvous and docking and on-board processing into one unit; promises to significantly reduce the mass and power requirements of the spacecraft. Guidance, navigation and control technological advances (e.g., MEMS based gyros and mini star trackers) and low-cost mass production facilities are all enabling, working together to meet the simultaneous mass and cost constraints of microspacecraft.

Table 1 Mars Microspacecraft Bus Mass Allocation

	2003 Mars Microspacecraft Mass Allocations (kilograms)			
	Science	Equa. Relay	Probe Carrier	
S/C Element	**Orbiter**	**Orbiter**		
C&DH/EPS				6 Cards, composite box, includes EPS switches
Power Supply				Solar Array & Li Battery (Ag Zn for Carrier)
Telecom				Includes SDST, HEF SSPA,
ACS				IMU, Star Camera, Sun Sensors
Thermal				MLI, strip heaters, coatings
Cabling				MFS Panels, flex connect
Structure				Primary and secondary structure, R&R
Mechanisms				HGA deploy and probe spin mech.
S/C Bus Mass, kg	**49.5**	**51.6**	**47.6**	
Press. System	5.9	5.9	5.9	Press. Tank and Pyros (with contingency)
Biprop. Components	15.2	15.2	15.2	Biprop tanks, thrusters, valves, lines
Payload	10.0	6.0	40.0	6 kg for UHF hardware
Total Dry,kg	**80.6**	**78.7**	**108.7**	
Press. Trapped Fuel	2.4	2.4	2.4	Helium gas and trapped fuel/ox
RCS Fuel	6.3	4.5	1.0	Fine pointing control with RCS thrusters
EOM Mass, kg	**89.3**	**85.6**	**112.1**	Mass used for ^{2}V calculation
Delta V Propellant	102.4	113.9	69.2	Orbiter 2415 m/s, Relay 2675, Probe 1520 m/s
Total Wet Mass, kg	**191.7**	**199.6**	**181.3**	**200 Kg Allowable**
Adapter	2.0	2.0	2.0	Assume GFE
Total Launch Mass	**193.7**	**201.6**	**183.3**	**202 Kg Allowable**
Launch Margin,kg	**8.3**	**0.4**	**18.7**	
2003 Assumptions				
3 year mission for sizing RCS fuel and solar arrays				
No reaction wheels				
SDST assumed for 2003				
Subsystem Masses include Contingency Growth based on Maturity				

4. SUMMARY

This paper has discussed some of the enabling technologies for a microspacecraft. High specific impulse propulsion systems, High-Density-Interconnect circuits, composite and inflatable structures, "flex-circuit-cabling", and aerobraking

In an all-out effort to reduce mass, cost constraints must also be challenged. The cost of the Mars Microspacecraft Bus was driven predominantly by a few costly components such as the transponder. For example, the cost of future planetary missions could be reduced if a lower cost telecommunications subsystem, such as the Space

Transponding Modem, is developed, in addition to other technologies being investigated or developed that promise to reduce recurring costs. The Applied Physics Lab has demonstrated techniques to eliminate the costly transponders by counting pulses. The APL receiver and transmitter card can be incorporated into an integrated avionics module to eliminate another dedicated electronics box.

The 2002 polar science mission and the polar relay orbiter mission can be accomplished with existing hardware and mass saving technologies that will be ready for the late 2002 launch. Table 1 gives a summary of the 2002 spacecraft mass for each mission configuration (with contingency mass included. Significant mass and cost savings are possible for the probe delivery mission since a lower cost battery and antenna can be used. The solar array can also be populated with fewer solar cells since the cruise phase requires about 50% less area than for an orbiter configuration. The current Lockheed Martin Astronautics design can meet all the mission requirements in 2002 and can also satisfy the requirements in 2005 and 2007 with selected technology insertion.

The Mars Micromission Spacecraft is based on a single string design to reduce mass and cost. Future studies continue to look at providing limited functional redundancy, e.g. use of RCS engines to backup main engines. Future reductions in electronics mass will allow added redundancy. The "Faster, Better, Cheaper" paradigm is being evolved such that a low-cost, quality product can be delivered on a reduced delivery schedule.

Development of a standard architecture and the utilization of a small project office team are essential to meeting performance goals. A modified peer review process streamlines development by reducing documentation and cost. LMA is committed to inserting selected enabling technologies and a new paradigm to successfully develop microspacecraft.

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[1] Lockheed Martin Astronautics Final Report: Feasibility and Concept Design Study for Mars MicroSpacecraft Bus, March 11, 1999.

Tim Gillespie is in Business Development for Lockheed Martin Flight Systems/Advanced Programs for the NASA Discovery Missions. Mr. Gillespie has worked on Boeing's Military Airplane as a Flight Deck Engineer and later transferred to the Boeing Advanced Concepts materials Development Group to support the Advanced Stealth Fighter project in developing threat resistant, low observable composites. In 1985, Mr. Gillepsie joined Martin Marietta Denver Aerospace as a Project Engineer in the Small ICBM Thermal Protection Materials (TPM) Development group and managed the Common TPM Test Program to evaluate TPM performance. In 1993, Mr. Gillespie accepted a position as a lead engineer in the Advanced Materials, Structures and Controls Group to develop thin film photovoltaic materials for lightweight solar arrays. Subsequently, Mr. Gillespie was named the Program Manager for the Lockheed Martin effort on the DARPA Vapor Phase Manufacturing of Thin Film Copper Indium DiSelenide (CIS) Flexible Photovoltaics Program. He has a BSME from the University of Nebraska in 1983.

Terry Gamber graduated from the University of Cincinnati in 1965 and has 37 years experience in mission design and spacecraft design on a wide range of missions including Viking, Magellan, Discovery and Surveyor. He has received a NASA Public Service award for his innovative mission design on Viking and commendations from JPL for his mission design interface role on Magellan. Terry has led Mars Sample Return studies over the last seven years where breakthrough concepts for a low mass Mars Ascent Vehicle and innovative gravity assist trajectories have been developed. He has also developed roadmaps for the Lockheed Martin Flight Systems Mission/Technology Strategy over the next ten years. He led the Mars Surveyor studies for the future missions from 2001 to 2005 including Mars Sample Return. He has led a study to accommodate the New Millennium microprobes on Mars '98. Mr. Gamber is currently a manager in Advanced Planetary Programs leading studies for future planetary missions.

Wendell Chun has been at Lockheed Martin Astronautics in Denver for the last twenty-one years, with the majority of his career in the robotics field for space, military, and environmental applications. He is also on Adjunct Faculty at the Colorado School of Mines' Engineering Division. Mr. Chun was the chief engineer for a wheeled rover and the walking-beam (seven-legged framewalker) for a future Mars exploration mission. In addition to mobile robots, Mr. Chun has developed unique manipulators for servicing and refueling. His current assignments include developing a mobile lander for a Mars sample return mission and developing technology for the rendezvous and docking of two spacecraft for automated servicing.

Professor Chun has a BSME from the University of Hawaii (Manoa) in 1978 and is a graduate of the Program in Engineering Design at the Carnegie Bosch Institute (1992). He was co-chair/editor of the SPIE Mobile Robots

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