Medical and Health-Care Robotics

Achievements and Opportunities

Celebrating
50 Years
of Robotics

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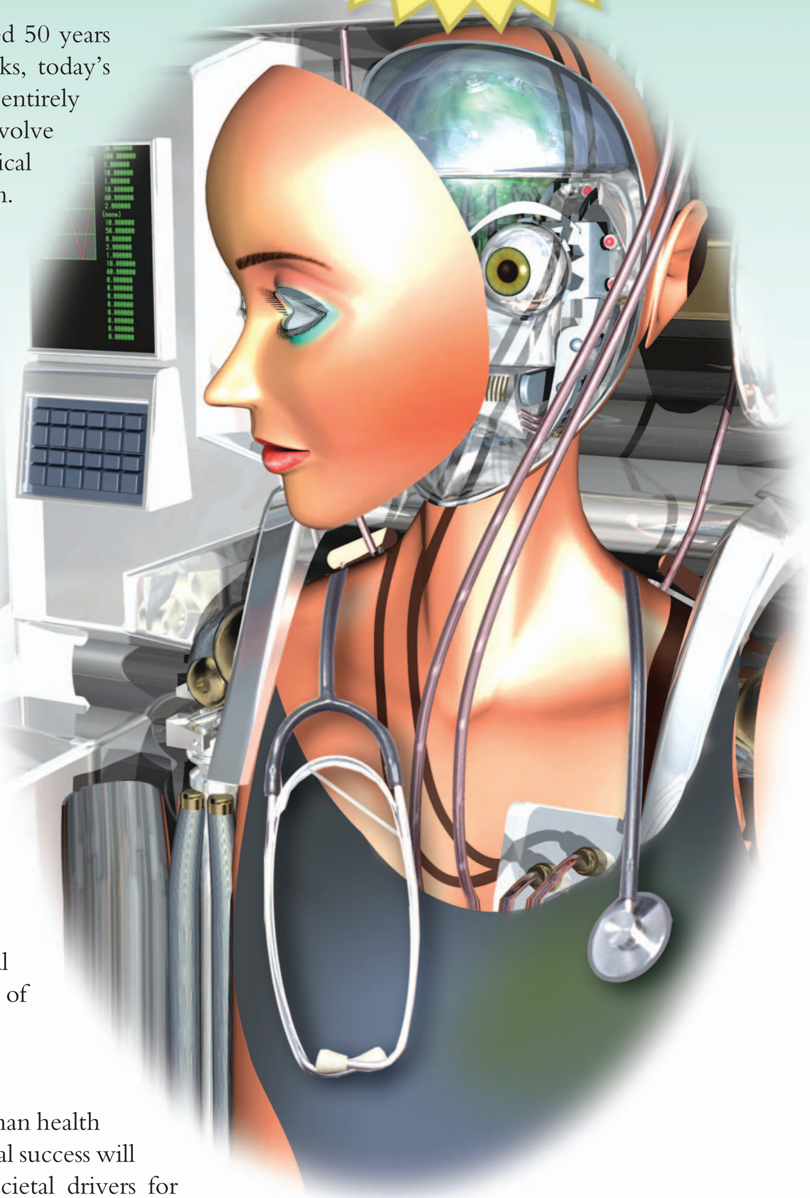
In contrast to the industrial robots, first developed 50 years ago, to automate dirty, dull, and dangerous tasks, today's medical and health-care robots are designed for entirely different environments and tasks—those that involve direct interaction with human users in the surgical theater, the rehabilitation center, and the family room. Commercial and research interest in medical and health-care robotics has seen substantial growth in the last decade. Telerobotic systems are being routinely used to perform surgery, resulting in shorter recovery times and more reliable outcomes in some procedures. Robotic rehabilitation systems are successfully delivering physical and occupational therapy, enabling a greater intensity of treatment that is continuously adaptable to a patient's needs. Socially assistive robotic (SAR) systems are being developed for in-clinic and in-home use in physical, cognitive, and social-exercise coaching and monitoring. Technological advances in robotics have the potential to stimulate the development of new treatments for a wide variety of diseases and disorders, improve both the standard and accessibility of care, and enhance patients' health outcomes. The aim of this article is to propose some of the most important capabilities and technical achievements of medical and health-care robotics needed to improve human health and well-being. We describe application areas, societal drivers, motivating scenarios, desired system capabilities, and fundamental research areas that should be considered in the design of medical and health-care robots.



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Design Considerations

Although robots are already beginning to affect human health through clinical use, further research and commercial success will be facilitated through careful consideration of societal drivers for

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improved health care, the specific capabilities that robotic systems should have to affect health-care scenarios, and the necessary fundamental technological improvements needed to achieve significant performance gains.

We begin this article by defining application areas and societal drivers for medical and health-care robots. Next, we briefly describe the motivation for using robots in specific application areas by highlighting a few examples of the existing approaches and providing motivating scenarios. Then we define desired system capabilities to achieve broader, more successful, and (in some application areas) initial application of robots in medicine and health care. We conclude with a list of basic research areas/technologies needed to achieve these capabilities. The article is based on the outcomes of a U.S. workshop and associated report titled "A Research Roadmap for Medical and Health-Care Robotics."

Application Areas for Medical and Health-Care Robots

Robots are already beginning to affect medicine (the application of science and technology to treat and prevent injury and disease) and health care (the availability of treatment and prevention of illness). Telerobotic systems are being used to perform surgery, resulting in shorter recovery times and more reliable outcomes in some procedures [1]–[3]. Robotic systems are also successfully delivering physical and occupational therapy [4], [5] and replacing lost limb function [6]. Experiments have also demonstrated that robotic systems can provide therapy oversight, coaching, and motivation that supplement human care with little or no supervision by human therapists and can continue long-term therapy in the home after hospitalization [7]–[11]. Creating a robotic system that mimics biology has been used as a way to study and test how the human body and brain functions [12]. Furthermore, robots can be used to acquire data from biological systems with unprecedented accuracy, enabling us to gain quantitative insights into both physical and social behavior.

The spectrum of robotic system niches in medicine and health care, thus, spans a wide range of environments (from the operating room to the family room), user populations (from the very young to the very old, from the infirm to the able bodied, from the typically developed to those with physical and/or cognitive deficits), and interaction modalities (from hands-on surgery to hands-off rehabilitation coaching).

Societal Drivers

Numerous societal drivers for improved health care can be addressed by robotic technology. Improving existing medical procedures to be less invasive and produce fewer side effects would result in faster recovery times and improved worker productivity. Revolutionary efforts to develop new medical procedures and devices, such as microscale interventions and smart prostheses, would substantially improve risk-benefit and cost-benefit ratios. More effective methods of training medical practitioners would lower the number of medical errors, as would objective approaches for accountability and certification/assessment. Ideally, these improvements would also lower costs to society by decreasing impact on families, caregivers, and employers.

Population factors related to economics must be considered. In the United States, more than 15% of the population is uninsured, and many others are underinsured. This prevents individuals from receiving the needed health care, sometimes resulting in loss of function or even life, and also prevents patients from seeking preventative or early treatment, resulting in worsening of subsequent health problems. Access to health care is most directly related to its affordability. Interactive therapy robots could reduce the cost of clinical rehabilitative care. The availability of SAR technologies [7] that could provide affordable in-home systems for motivating and coaching physical and cognitive exercise would positively impact both prevention and rehabilitation. Finally, robotics technologies for caretaking of the elderly can promote aging in place (i.e., at home), delay the onset of dementia, and provide companionship to mitigate isolation and depression.

Access to health care is also related to location. When disasters strike and result in human injury, distance and unstructured environments are obstacles to providing on-site care and removing the injured from the scene in both natural disasters (e.g., earthquakes and hurricanes) and man-made disasters (e.g., terrorist attacks). Similar problems occur in the battlefield; point-of-injury care is needed to save the lives of many military personnel. Some environments, such as space, undersea, and underground (for mining) are inherently far from medical personnel. Finally, rural populations can live prohibitively far from medical centers that provide specialized health care. Robots can provide access to treatment for people outside populated areas and in disaster scenarios.

Population factors indicate a growing need for improved access and quality of health care. Demographic studies show that many countries will undergo a period of significant population aging over the next several decades. By 2030, the United States, Europe, and Japan will experience increases of approximately 40, 50, and 100%, respectively, in the number of elderly, as shown in Figure 1 [14]. The number of people with an age above 80 will increase by more than 100% across all continents. Advances in medicine have increased the life span; this

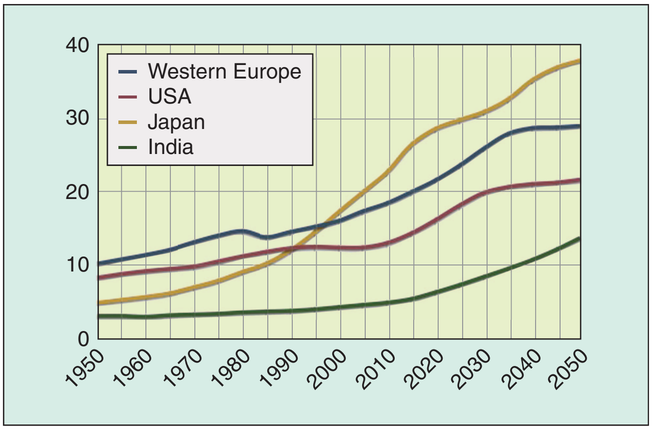

Figure 1. *Past and anticipated percentage of the population above age 65 [14].*

in combination with reduced birthrates will result in an aging of society in general. This demographic trend will have a significant impact on industrial production, housing, continued education, and health care. Associated with the aging population is increased prevalence of injuries, disorders, and diseases. Across the age spectrum, there are significant increases in lifelong conditions, including diabetes, autism, obesity, and cancer.

These trends are expanding the need for personalized health care. For example, the current rate of new strokes in the United States is 800,000 per year, and that number is expected to double in the next two decades. Patients with stroke must engage in intensive rehabilitation to regain function and minimize permanent disability. While stroke is most prevalent among older patients, cerebral palsy (CP) is prevalent among children. About 8,000 infants are diagnosed with CP each year, and more than 760,000 persons in the United States manifest symptoms of CP. Further, the number of neurodevelopmental and cognitive disorders is on the rise, including autism spectrum disorder, attention deficit, and hyperactivity disorder. Autism rates alone have quadrupled in the last quarter century, with one in 100 children diagnosed with the deficit today. Improved outcomes from early screening and diagnosis, transparent monitoring, and continual health assessment will lead to greater cost savings, as can effective personalized technology-aided intervention and therapy. These factors will also offset the shrinking size of the health-care workforce, while affordable and accessible technology will facilitate wellness and personalized/home-based health care.

Increasing lifelong independence thus becomes a key societal driver. It includes enabling aging in place, improving mobility, as well as reducing isolation and depression at all ages (which in turn impact productivity, health costs, and well-being). Improving care and empowering the care recipient also facilitates providing independence for caregivers who are increasingly employed. Such care is increasingly informal because the economics of in-home health care are unaffordable. Lifelong health education and literacy facilitates prevention and can be augmented by improved safety and monitoring to avoid mismedication, ensure consistency in taking medication, and monitoring for falls, lack of activity, and other signs of decline.

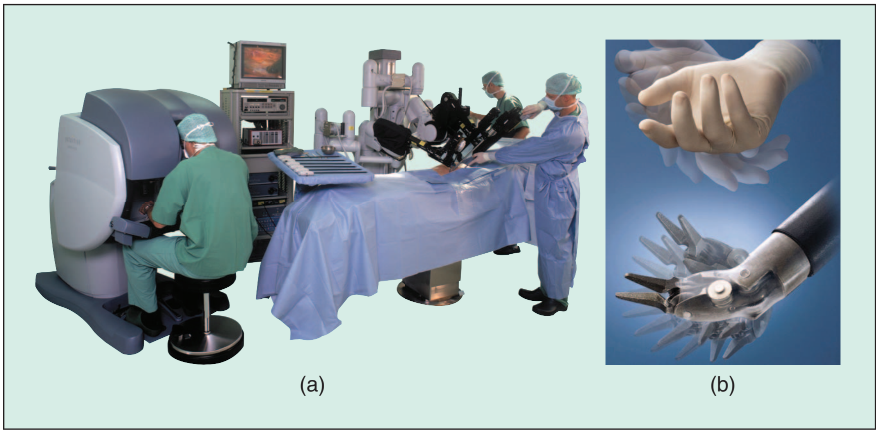
(a)
(b)

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Figure 2. (a) The da Vinci surgical system consists of a master console and teleoperated patient-side robot. (b) Dexterous instruments enable fine manipulation inside the body.

Motivations for Medical Robotics

We now briefly review the current potential for specific applications of medical and health-care robotics and provide motivating scenarios for current and future research efforts.

Surgical and Interventional Robotics

The development of surgical robots is motivated by the desire to enhance the effectiveness of a procedure by coupling information to action in the operating room or interventional suite and transcend human physical limitations in performing surgery and other interventional procedures, while still affording human control over the procedure. Two decades after the first reported robotic surgical procedure, surgical robots are now being widely used in the operating room or interventional suite. Surgical robots such as the da Vinci surgical system in Figure 2 are beginning to realize their potential in terms of improved patient outcomes.

Current robots used in surgery are under the direct control of a surgeon, often in a teleoperation scenario in which a human operator manipulates a master input device, and patient-side robot follows the input. In contrast to traditional minimally invasive surgery, robots allow the surgeon to have dexterity inside the body, scale-down operator motions from normal human dimensions to very small distances, and provide an intuitive connection between the operator and the instrument tips. A complete surgical workstation contains both robotic devices and real-time imaging devices to visualize the operative field during the course of surgery. The next generation of surgical workstations will provide a wide variety of computer and physical enhancements, such as no-fly zones around delicate anatomical structures, seamless displays that place relevant data in surgeon's field of view, and recognition of surgical motions and patient state to evaluate performance and predict outcomes.

If the right information is available, many medical procedures can be planned ahead of time and executed in a reasonably predictable manner, with the human exercising mainly supervisory control over the robot. Examples include preparation of bone for joint reconstructions in orthopedic surgery and placement of needles into targets in interventional radiology. In these cases, the level of automation may vary, depending on the task and the relative advantage to be gained. As imaging, tissue modeling, and needle-steering technologies improve, future systems are likely to become more highly integrated and actively place therapy devices through paths that cannot be achieved by manual insertion. In these cases, the human will identify the target, plan or approve the proposed path, and supervise the robot as it acquires the target.

Robotic Replacement of Diminished/Lost Function

Orthoses protect, support, or improve the function of various parts of the body, usually the ankle, foot, knee, and spine.

Unlike robotic devices, traditional orthoses are tuned by experts and cannot automatically modify the level or type of assistance as the patient grows and his or her capabilities change. Robotic orthoses are typically in the form of an exoskeleton, which envelopes the relevant body part. They must allow free motion of limbs while providing the required support. Most existing robotic exoskeletons are research devices that focus on military applications (e.g., to allow soldiers to carry heavy loads on their backs) and rehabilitation in the clinic. However, these systems are not yet inexpensive and reliable enough for use as orthoses by patients.

Prosthesis is an artificial extension that replaces the functionality of a body part (typically lost by injury or congenital defect) by fusing mechanical devices with human muscle, skeleton, and nervous systems. Existing commercial prosthetic devices are very limited in capability (typically allowing only opening/closing of a gripper) because they are signaled to move purely mechanically or by electromyography (EMG), which is the recording of muscle electrical activity in an intact part of the body). Robotic prosthetic devices aim to more fully emulate the missing limb or other body part through replication of many joints and limb segments (such as the 22 degrees of freedom of the human hand) and seamless neural integration that provides intuitive control of the limb as well as touch feedback to the wearer (Figure 3). The last few years have seen great strides in fundamental technologies and neuroscience that will lead to these advanced prostheses. Further robotics research is needed to vastly improve the functionality and affordability of prostheses.

Robot-Assisted Recovery and Rehabilitation

Patients suffering from neuromuscular injuries or diseases often benefit from neurorehabilitation. This process exploits the use-dependent plasticity of the human neuromuscular system, in which use alters the properties of neurons and muscles, including the pattern of their connectivity, and thus their function. Sensory motor therapy, in which a patient makes upper extremity or lower extremity movements physically assisted (or resisted) by a human therapist and/or robot, helps people relearn how to move. This process is time-consuming and labor-intensive but pays large dividends in terms of patient health-care costs and return to productive labor. As an alternative to human-only therapy, a robot has several key advantages: 1) after set up, the robot can provide consistent, lengthy, and personalized therapy without tiring; 2) the robot can acquire data to provide an objective quantification of recovery; and 3) the robot can implement therapy exercises not possible by a human therapist. There are already significant clinical results from the use of robots to retrain upper- and lower-limb movement abilities for individuals who have had neurological injury, such as cerebral stroke. These rehabilitation robots provide many different forms of mechanical input, such as assisting, resisting, perturbing, and stretching, based on the subject's real-time response. For example, the Massachusetts Institute of Technology (MIT)-Manus rehabilitation robot (now a commercial product, Figure 4) showed improved recovery of both acute and chronic stroke patients. Another exciting implication of sensory-motor therapy with robots is that they can help neuroscientists improve their general understanding of brain function. Through robot-based perturbations to the patient and quantification of the response, robots can make useful stimulus-response recordings.

In addition to providing mechanical/physical assistance in rehabilitation, robots can also provide personalized monitoring, motivation, and coaching. SAR focuses on using sensory data from wearable sensors, cameras, or other means of perceiving the user's state to provide the robot with information that allows the machine to appropriately encourage and motivate sustained recovery exercises. Early work has demonstrated such SARs in the stroke rehabilitation domain, and they are being developed for other domains including traumatic brain injury. In addition to long-term rehabilitation, these systems also have the potential to impact health outcomes in short-term convalescence where intensive regiments are prescribed. For example, an early system was demonstrated in the cardiac ward, encouraging and coaching patients to perform spirometry exercises ten times per hour. Such systems can serve not only as force multipliers in heath-care delivery, providing more care to more patients, but also as a means of delivering

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Figure 3. *An advanced prosthetic arm with targeted reinnervation-based myoelectric control.*

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Figure 4. *The InMotion 2.0 Shoulder Robot is a commercially available rehabilitation robot.*

personalized medicine and care, providing more customized care to all patients.

Behavioral Therapy

Convalescence, rehabilitation, and management of lifelong cognitive, social, and physical disorders require ongoing behavioral therapy, consisting of physical and/or cognitive exercises that must be sustained at the appropriate frequency and correctness. In all cases, the intensity of practice and self-efficacy has been shown to be the keys to recovery and minimization of disability. However, because of the fast-growing demographic trends of many of the affected populations, the available health care needed to provide supervision and coaching for such behavior therapy is already lacking and on a recognized steady decline.

SAR is a comparatively new field of robotics that focuses on developing robots aimed at addressing precisely this growing need. SAR is developing systems capable of assisting users through social rather than the physical interaction. The robot's physical embodiment (Figure 5) is at the heart of SAR's assistive effectiveness, as it leverages the inherently human tendency to engage with lifelike (but not necessarily human-like or animal-like) social behavior. People readily ascribe intention, personality, and emotion to even the simplest robots. SAR uses this engagement to develop robots capable of monitoring, motivating, encouraging, and sustaining user activities and improving human performance. SAR thus has the potential to enhance the quality of life for large populations of users, including the elderly, individuals with cognitive impairments, those rehabilitating from stroke and other neuromotor disabilities, and children with sociodevelopmental disorders such as autism. Robots, then, can help to improve the function of a wide variety of people and can do so not just functionally but also socially, by embracing and augmenting the social and emotional connection between the human and robot.

Human–robot interaction (HRI) for SAR is a growing multifaceted research area at the intersection of engineering, health sciences, psychology, social science, and cognitive science. An effective socially assistive robot must understand and interact with its environment, exhibit appropriate social behavior, focus its attention and communication on the user, sustain engagement with the user, and achieve specific assistive goals. These goals are achieved through social rather than physical interaction, in a way that is safe, ethical, and effective for the potentially vulnerable user. Socially assistive robots have already been shown to have promise as therapeutic tool for children, the elderly, stroke patients, and other special-needs populations requiring personalized care, which is discussed next.

AIST, JAPAN. IMAGE © 2010 ANTHROTRONIX, INC.

Figure 5. Socially interactive robots for behavioral therapy, personalized care, and wellness/health promotion. (a) Paro, a huggable baby harp seal robot designed for use in hospitals and nursing homes. (b) CosmoBot, a robot designed for play therapy for children with developmental disorders.

Personalized Care for Special-Needs Populations

The growth of special-needs populations, including those with physical, social, and/or cognitive disorders, which may be developmental, early onset, age related, or occur at any stage of life, present a growing need for personalized care. Some of the pervasive disabilities are congenital (from birth), such as CP and autism spectrum disorder, while others may occur at any point during one's lifetime (traumatic brain injury and stroke), and still others occur later in life but persist longer with the extended lifespan (Parkinson's disease, dementia, and Alzheimer's disease). In all cases, these conditions are lifelong, requiring long-term assistance.

Physical mobility aids, ranging from devices for the visually impaired to the physically disabled and from high-end intelligent wheelchairs to simpler self-stabilizing canes, expand accessibility to goods and services and decrease isolation and the likelihood of depression and the need for managed care. Robotic technologies promise mobility aids that can provide adjustable levels of autonomy for the user, so one can choose how much control to give up, a key issue for users with disabilities. Intelligent wheelchairs, guide-canes, and interactive walkers are just a few illustrations of systems that have been developed and are, in a few cases, already commercially available.

With the fast-growing elderly population, the need for devices that enable individuals with physical limitations and disabilities to continue living independently in their own homes is soaring. This need is augmented not only by the needs of the smaller but also growing population of the physically disabled, including war veterans. Complex systems for facilitating independence, such as machines that aid in manipulation and/or mobility for the severely disabled, and those that aid complex tasks such as personal toiletry and getting in/out of bed, are still in the early stages of development but show promise of fast progress. At the same time, mobile robotics research is advancing the development of mobile manipulation platforms toward machines capable of fetching and delivering household items, opening doors, and generally facilitating the user's ability to live independently in his/her own home. The delay (or elimination, if possible) of the need for moving an individual to a managed-care facility significantly decreases the cost and burden on the individual, family, and health-care providers. It also greatly diminishes the likelihood of isolation, depression, and shortened lifespan.

In addition to physical/mechanical aid, special-needs populations stand to benefit significantly from advances in SAR (discussed in the previous section), which provide personalized monitoring, companionship, and motivation for cognitive and physical exercises associated with lifelong health promotion.

Wellness/Health Promotion

Improved prevention and patient outcomes are broad and fundamental goals of health care. Better, more effective, more accessible, and personalized ways of encouraging people to eat right, exercise, and maintain mental health would significantly decrease many urgent and chronic health issues.

Despite its fundamental importance, health promotion receives less attention and significantly fewer resources than health intervention. Research funding is justifiably aimed at efforts to seek causes and cures for diseases and conditions, rather than on their prevention, with the exception of vaccine research in specific subareas [e.g., cancer and acquired immune deficiency syndrome (AIDS)]. However, prevention-oriented research and its outcomes have the potential to most significantly impact health trends and the associated major costs to society. Insurance companies are particularly motivated to promote prevention and to invest in technologies that do so. Although they may not be positioned to support basic research, they are willing to support evaluation trials of new technologies oriented toward prevention and health promotion.

Robotics technologies are being developed to address wellness promotion. Many of the advances described earlier also have extensions and applications for wellness. Specifically, robotic systems that promote, personalize, and coach exercise (whether through social and/or physical interaction) as well as provide companionship have large potential application niches from youth to the elderly (Figure 5), from able-bodied to disabled, and from amateurs to trained athletes. Some such systems have been commercialized (e.g., Figure 5), and there is growing interest in further development given the expected demand on the consumer market. Wearable devices that monitor physiologic responses and interact with robotic and computer-based systems also have the potential to promote personalized wellness regiments and facilitate early detection and continuous assessment of disorders. In this context, robotics is providing enabling technologies that interoperate with existing systems (e.g., laptop and desktop computers, wearable devices, and in-home sensors) to leverage advances across fields and produce a broad span of usable technologies toward improving quality of life.

Desired System Capabilities

To address the health-care challenges noted in the "Robotic Design Considerations" and "Motivations for Medical Robotics" sections, we present a list of major capabilities that robotic systems must have for ideal integration into medicine and health care. These capabilities, in turn, motivate the basic research areas listed in the "Necessary Basic Research/Technologies" section (Figure 6).

Intuitive Physical HRI and Interfaces

The use of robotics in medicine inherently involves physical interaction between caregivers, patients, and robots—in all combinations. Developing intuitive physical interfaces between humans and robots requires all the classic elements of a robotic system: sensing, perception, and action. A great variety of sensing and perception tasks are required, including recording the motions and forces of a surgeon to infer their intent, determining

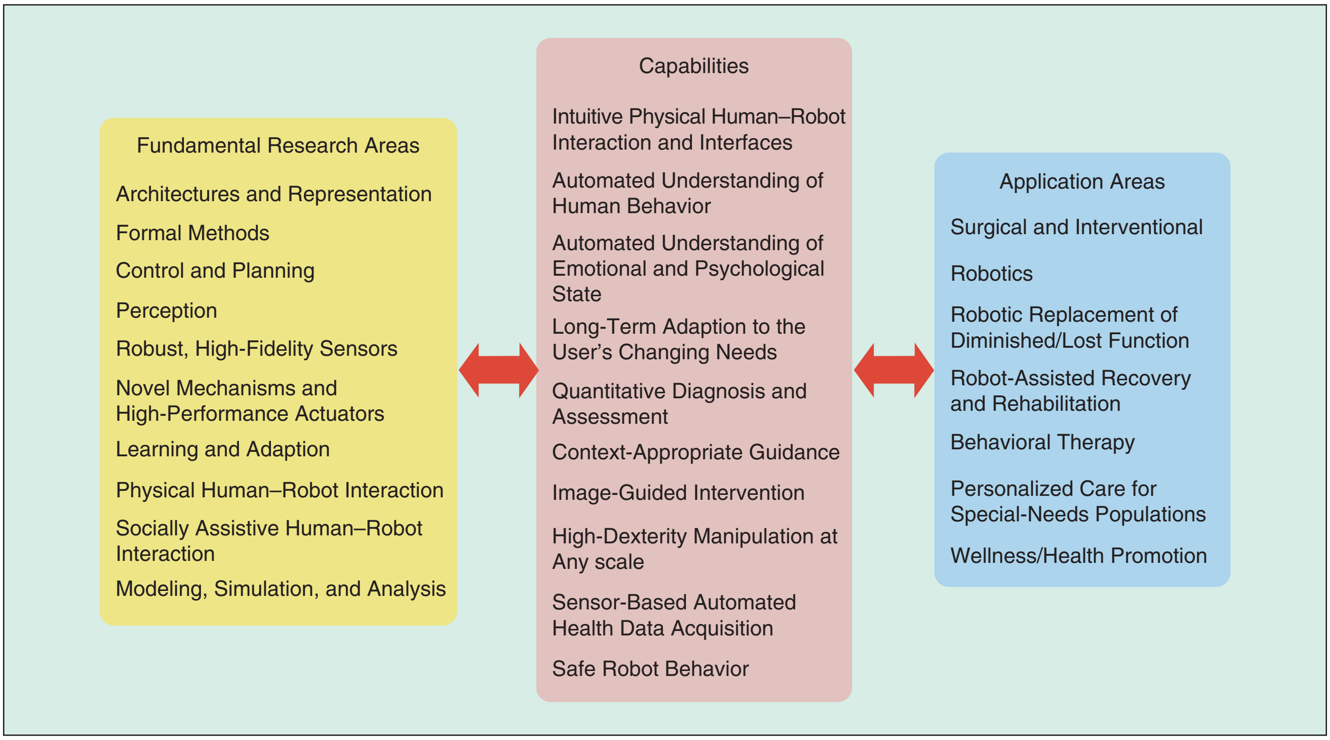

Figure 6. *Fundamental robotics research topics relate to system capabilities, which in turn affect the performance of medical and health-care robots.*

The next generation of surgical workstations will provide a wide variety of computer and physical enhancements.

the mechanical parameters of human tissue, and estimating the forces between a rehabilitation robot and a moving stroke patient. The reciprocal nature of interaction means that the robot will also need to provide useful feedback to the human operator, a caregiver, or a patient. We need to consider systems that involve many human senses, the most common of which are vision, haptics (force and tactile), and sound.

The action of a robot as felt by the user is inherently related to the mechanical/mechatronic design of the robot, since sensing and control can only change the feel of a robot to a certain degree. The development of innovative mechanically backdrivable systems with high kinematic efficiency, which display low apparent dynamics (e.g., inertia) to the user, is important for safety and efficacy in many medical and health-care applications. Such designs are especially challenging for systems that must match the complex geometry of the human body (e.g., exoskeletons).

A major reason why systems involving physical collaboration between humans and robots are so difficult to design well is that, from the perspective of a robot, humans are extremely uncertain. Humans change their motion, strength, and immediate purpose on a regular basis. This can be as simple as physiologic movement (e.g., a patient breathing during surgery) or as complex as the motions of a surgeon suturing during surgery. During physical interaction with a robot, the human is an integral part of a closed-loop feedback system, simultaneously exchanging information and energy with the robotic system, and thus cannot simply be thought of as an external system input. In addition, the loop is often closed with both human force and visual feedback, each with its own errors and delays; this can potentially cause instabilities in the human–robot system. Given these problems, how do we guarantee safe, intuitive, and useful physical interaction between robots and humans? There are several approaches to solving these problems, which can be used in parallel: modeling the human with as much detail as possible, sensing the human's physical behavior in a very large number of dimensions, and developing robot behaviors that will ensure appropriate interaction no matter what the human does. Great strides have been made in these areas over the last two decades; yet there are still no systems that provide the user with an ideal experience of physically interacting with a robot.

Automated Understanding of Human Behavior

Understanding the user's activity and intent are necessary components of HRI, for machines to respond appropriately and in a timely and safe fashion. Because human activity is complex and unpredictable, and because vision-based perception is an ongoing challenge in robotics, automated perception and understanding of human behavior require the integration of data from a multitude of sensors, including those on the robot, in the environment, and worn by the user. Research into algorithms for real-time, online, multimodal sensor integration is under development, including the application of statistical methods for user modeling based on multimodal data. Recognition and classification of human activity and intent is of particular interest to enable real-time user interaction and assistance. HRI systems will only be accepted by users if they are responsive on a time-scale that each user finds reasonable (i.e., the system cannot respond too quickly, take too long to respond, nor can it respond incorrectly too often). Current methods for multimodal perception have used various means of simplifying the hard problems of real-world object and person recognition and activity recognition and classification. For example, efforts have used colored and reflective markers, bar codes, and radiofrequency (RF) identification tags, all of which require some level of instrumentation of the environment. Minimizing such instrumentation and making it nonintrusive is a necessary aspect of making the technology acceptable.

Continued progress in automated understanding of human behavior will require advances in 1) the use of physiologic sensing as a counterpart to standard on-robot and in-environment sensing; 2) leveraging, processing, and using multimodal sensing on the robot, in the environment, and on the user for real-time HRI; and 3) understanding of user affect/emotion.

Automated Understanding of Emotional and Physiological State

The ability to automatically recognize emotional states of users in support of appropriate, personalized robot behavior is critical for making personalized robotics effective, especially for health-related applications that involve vulnerable users. Emotion recognition has been studied in voice and speech signals, facial data, and physiologic data. Given the complexity of the problem, emotion understanding, modeling, and classification will directly benefit from strides in all of the areas listed earlier: activity recognition, physiologic data processing, and multimodal perception. Emotion understanding requires processing multichannel data from the user, and reconciling inconsistencies (e.g., between verbal versus facial signals). The power of empathy is well recognized in health care: doctors who are perceived as empathetic are judged as most competent and have the fewest lawsuits. Creating empathy in synthetic systems is just one of the challenges of perceiving and expressing emotion. Furthermore, early work in SAR has demonstrated that personality expression, related to emotion, is a powerful tool for coaching and promoting desired behavior from a user of a rehabilitation system. Since personality is known to have impact on health outcomes, the ability to perceive, model, and express it and the associated emotions is an important aspect of human–machine interaction aimed at improving human health and quality of life.

Physiologic data, such as measures of frustration, fatigue, and interest, are invaluable in understanding the state of the user and enabling robots to assist the user and optimize performance. Physiologic data sensors are typically wearable devices that provide real-time physiologic signals (e.g., heart rate, galvanic skin response, and body temperature). These signals are highly individualized and typically complex to visualize and analyze. Active research in the field is addressing methods for extracting metrics, such as frustration and saliency relative to external activity, from physiologic data. Research is also focusing on connecting and accessing bioelectrical signals with wearable or implantable devices. With the exception of some implantable devices, lightweight wearable sensors with wireless capabilities for data transmission and low-weight batteries are not yet readily available. The promise of wearable sensory technologies has been recognized widely and developments toward addressing these issues are in progress. The ability to capture physiologic data in an unencumbering way and transmit those data to a computer, robot, or caregiver has great potential for improving health assessment, diagnosis, treatment, and personalized medicine.

Long-Term Adaptation to the User's Changing Needs

The need for system adaptation and learning is especially evident in HRI domains. Each user has specific characteristics, needs, and preferences to which the system must be attuned. Furthermore, those very characteristics, needs, and preferences can change over time as the user gets accustomed to the system and as the health state of the user changes, over the short term (convalescence), medium term (rehabilitation), and life (lifestyle changes, aging). To be accepted, usable, and effective, robot systems interacting with human users must be able to adapt and learn in new contexts and at extended time-scales, in a variety of environments and contexts.

Challenges in long-term learning include the integration of multimodal information about the user over time, in light of inconsistencies and changes in behavior, and unexpected experiences. Machine learning, including robot learning, has been adopting increasingly principled statistical methods. However, the work has not yet addressed the complexities of real-world uncertain data (noisy, incomplete, and inconsistent), multimodal data about a user (ranging from signal-level information from tests, probes, electrodes, and wearable devices to symbolic information from charts, questionnaires, and patient interviews), and long-term data (over months and years of treatment).

The ability to interact with the user through intuitive interfaces (gestures, wands, and speech) and learn from demonstration and imitation have been topics of active research. They present a novel challenge for in-home long-term interactions where the system is subject to user learning and habituation, as well as diminishing novelty and patience effects. Robotic learning systems have not yet been tested on truly long-term studies, and lifelong learning is not yet more than a concept. Because learning systems are typically difficult to assess and analyze, it is important that such personalized, adaptive technologies be equipped with intuitive visualization of system state as well as user health state.

Taking these challenges into account, an ideal adaptive, learning health-care robot system would be able to predict changes in the health state of the user/patient and adjust the delivery of its services accordingly; it would adjust its methods for motivating, encouraging, and coaching the user continually to retain its appeal and effectiveness by sustaining user engagement over the long term. Such a system would have quantitative metrics to show positive health outcomes based on health professional-prescribed convalescence/intervention/therapy/prevention methods.

Convalescence, rehabilitation, and management of lifelong cognitive, social, and physical disorders require ongoing behavioral therapy.

Quantitative Diagnosis and Assessment

Robots coupled to information systems can acquire data from patients in unprecedented ways. They can use sensors to record the physiologic status of the patient, engage the patient in physical interaction to acquire external measures of health such as strength, and interact with the patient in social ways to acquire behavioral data (e.g., eye gaze, gesture, and joint attention) more objectively and repeatedly than a human observer could. In addition, the robot can be made aware of the history of the particular health condition and its treatment and be informed by sensors of the interaction that occur between the physician or caregiver and the patient. Quantitative diagnosis and assessment requires sensing of the patient, application of stimuli to gauge responses, and the intelligence to use the acquired data for diagnosis and assessment. When diagnosis or assessment is uncertain, the robot can be directed to acquire more appropriate data. The robot should be able to interact intelligently with the physician or caregiver to help them make a diagnosis or assessment with sophisticated domain knowledge, not necessarily replace them. As robots facilitate aging in place, automated assessment becomes more important as a means to alert a caregiver, who may not always be present, about potential health problems.

Each myriad step in diagnosis/assessment needs to be improved and then combined into a seamless process. These steps include: apply stimulus (if necessary), acquire data, make a diagnosis or assessment of patient health, relay the information in a useful form with appropriate level of detail to a caregiver, integrate caregiver input to revise diagnosis/assessment, and perform actions that will allow collection of more or different data (if needed) to make a better informed diagnosis/assessment. In some settings, this process is self-contained (i.e., administered within a controlled session), whereas in others, it may be a more open-ended procedure (i.e., administered in a natural environment, such as the home).

Context-Appropriate Guidance

Robots can provide context-appropriate guidance to human patients and caregivers, combining the strengths of the robot (accuracy, dexterity at small scales, and advanced sensory capabilities) with the strengths of the human (domain knowledge, advanced decision making, and unexpected problem solving).

SAR is a comparatively new field of robotics that focuses on developing affordable noncontact systems for providing motivating, monitoring, and coaching physical and cognitive exercise and companionship for a broad range of user populations.

This shared-control concept is also known as human–machine collaborative systems, in which the operator works in-the-loop with the robot during the task execution. As described earlier, humans (both patients and caregivers) represent uncertain elements in a control system. Thus, for a robot to provide appropriate assistance, it is essential that a robot understands the context of the task and the human behavior, for tasks such as grasping an object with a prosthetic hand, performing a delicate surgical procedure, or assisting an elderly patient to get out of bed.

Many types of assistance/guidance can be provided. In prosthesis control, it may be decades before we have sufficient understanding of the human nervous system to provide sensory feedback that allows humans to easily control an artificial hand with as many joints as a real hand. Thus, low-level robotic controllers are needed to automatically control the joints that are not directly controlled by the human. Another example is surgical virtual fixtures, which are a general class of guidance modes, implemented in software and executed by a robotic device, that help a human–machine collaborative system perform a task by limiting movement into restricted regions and/or influencing movement along desired paths. Virtual fixtures can ensure (or just encourage) that the manipulator inside the patient does not enter forbidden areas of the workspace, such as organ surfaces that should not be cut and delicate tissue structures. A final example of such guidance includes coaching of physical, cognitive, and/or social exercises toward rehabilitation of a variety of conditions. Implementing such guidance modes requires that the robot understands the task the human operator or user is trying to do, the current state of the human (both physically and the human's intent), and have the physical and/or social means for providing assistance.

Image-Guided Intervention

Robotic image-guided intervention concentrates on visualization of the internal structures of a patient to guide a robotic device and/or its human operator. This is usually associated with surgery and interventional radiology, although the concepts described here could more broadly apply to any health-care needs in which the patient cannot be naturally visualized. No matter the application, such interventions require advances in image acquisition and analysis, development of robots that are compatible with imaging environments, and methods for the robots and their human operators to use the image data.

Sensor data are essential for building models and acquiring real-time information during surgery and interventional radiology. Real-time medical imaging techniques such as magnetic resonance imaging (MRI), ultrasound, spectroscopy, and optical coherence tomography (OCT) can provide significant benefits. They enable the physician to see subsurface structures and/or tissue properties. In addition, images acquired preoperatively can be used for planning and simulation. New techniques such as elastography, which noninvasively quantifies tissue compliance, are needed to provide images that provide useful, quantitative physical information. The speed and resolution of medical imaging technology needed for various robot-control strategies have not yet been defined. We should determine how to optimally integrate medical imagers with robotic systems to provide useful information to the surgeon and enable the robot to react to patient health in real time.

One of the most useful forms of imaging is MRI. The design of MRI-compatible robots is especially challenging because MRI relies on a strong magnetic field and RF pulses, and so it is not possible to use components that can interfere with, or be susceptible to, these physical effects. This rules out most components used for typical robots, such as electric motors and ferromagnetic materials. In addition, surgery or interventional radiology inside an imager places severe constraints on robot size and geometry, as well as the nature of the clinician–robot interaction. Novel materials, actuation mechanisms, and sensors are required to create robots that can be seamlessly integrated into the interventional suite.

High-Dexterity Manipulation at Any Scale

Device design and control is key to the operation of all medical and health-care robotics, since they interact physically with their environment. Accordingly, one of the most important technical challenges is in the area of mechanisms. For example, in surgical applications, the smaller a robot is, the less invasive the procedure is for the patient. In most procedures, increased dexterity results in more efficient and accurate surgeries. One can even consider the possibility of cellular-scale surgery; proofs-of-concept of this have already been implemented in the laboratory. Another example is rehabilitation: current rehabilitation robots are large and relegated to the clinic. Similarly, human physical therapists have limited availability. Yet for many patients, effective long-term therapy clearly calls for longer and more frequent training sessions than is affordable or practical in the clinic. Human-scale wearable devices, or at least ones that can be easily carried home, would allow rehabilitative therapies to be applied in unprecedented ways. Finally, consider a dexterous prosthetic hand. To fully replicate the joints of a real hand, using current mechanisms, actuator designs, and power sources, would require the hand to be too heavy or large for a human to naturally use. Small, dexterous mechanisms would make great strides toward more lifelike prosthetic limbs.

Miniaturization is challenging in large part because current electromechanical actuators (the standard because of their desirable controllability and power to weight ratio) are relatively large. Biological analogs (e.g., human muscles) are far superior to engineered systems in terms of compactness, energy efficiency, low impedance, and high force output. Interestingly, these biological systems often combine mechanisms and actuation into an integrated, inseparable system. Novel mechanism design will go hand in hand with actuator development. In addition, every actuator/mechanism combination will need to be controlled for it to achieve its full potential behavior, especially when dexterity is required. Models need to be developed to optimize control strategies; this may even motivate the design of mechanisms that are especially straightforward to model.

Sensor-Based Automated Health Data Acquisition

We are approaching an age of nearly pervasive perception. Cameras are cheap, and getting cheaper, and image analysis algorithms are getting better. The networking infrastructure continues to improve. For whatever purpose (home security and petcams), it is likely that significant parts of our lives will be observed by the resulting sensor network. Other sensors are also becoming more effective and more common. Our cell phones include accelerometers, cameras, and global positioning system (GPS), which provide considerable information. Added to this the rapid growth in more conventional medical imaging and the possibility of other biosensors, such as wearable monitors or ingested cameras and instrumented toilets, it becomes technically feasible for each of us to have a detailed record, covering nutrition, behavior, and physiology.

Aggregating over the entire population, we will have a database vastly more detailed and broader in scope than anything we have seen in the past. Such a database enables a new level of medical research based entirely on historical data. At present, medical studies are targeted to address specific issues or hypotheses, and the cost of these studies restricts the scope and duration. There are also some types of data, such as behavior patterns in one's normal life, that are very difficult to obtain at present. A large-scale database enables more open-ended research, identifying patterns, or correlations that may never have been suspected. It also brings a new level of personalized health care, providing speedier and more accurate diagnoses, as well as a source of advice on lifestyle choices and their likely consequences.

Safe Robot Behavior

The challenge of safe robot action and reaction is as old as the field of robotics itself. However, safety takes on a new dimension when directly close-up interactions with human users, often vulnerable ones, constitute the core of the robot's purpose. Providing appropriate response to human behavior (e.g., knowing difference between inadvertent human behavior and specific intent) represents a new technical challenge.

The robot must be able to anticipate dangerous behavior or conditions (i.e., create virtual constraints) and respond to any urgent conditions in home environments under all conditions. Such operation is much more readily achieved in noncontact systems, i.e., HRI that does not involve physical touch and application of force between the user and the robot. When contact is involved, research is focusing on inherently safe mechanisms at the mechanical and hardware level to facilitate safety well before the software level.

Natural, unconstrained human behavior is complex, notoriously unpredictable, and fraught with uncertainty.

Safety of behavior has more profound implications than merely physical interaction. While SARs does not typically involve any physical contact between the robot and the user, the interaction may result in strong attachment, dependence, or aversion. These possibilities must be taken into account in the context of safe system design.

Necessary Basic Research/Technologies

Significant advances by robotics researchers are necessary to realize the capabilities described in the "Desired System Capabilities" section. This section briefly describes the areas identified as most essential to advancing the capabilities of medical and health-care robots.

Architectures and Representations

Robot control architectures encapsulate organizational principles for proper design of programs that control robot systems. The development of robot control architectures has reached a new level of complexity with medical and health-care robotic systems, because such systems must interact, in real time, with complex real-world environments, ranging from human tissue to human social interactions. To address these challenges, architectures must be developed to facilitate principled programming for agile, adaptive systems for uncertain environments involving direct physical and/or nonphysical interactions with one or multiple human users.

Formal Methods

Formal methods are mathematical approaches for the specification, development, and verification of systems. For medical robots that interact directly with human caregivers and patients, controller designs, planners, operating software, and hardware should be verified and validated as safe using formal methods. At this time, most work in formal methods does not incorporate uncertainty to the extent that is needed for medical and health-care robotics. A related goal is the use of formal methods in the design and modeling the behavior of systems that work with humans.

Control and Planning

Control is an essential component of all physical robots. In medical robotics, a particularly important aspect of control is contact/force control. Maintaining stable, safe contact is challenging because of time delays and imperfect dynamic models. All of these problems need to be addressed through improvements in robot design, modeling, and control. Planning for medical and health-care robotics requires new

Prevention-oriented research and its outcomes have the potential to most significantly impact health trends and the associated major costs to society.

approaches for operation in uncertain environments and with human input.

Perception

Robot perception, which uses sensor data and models to develop an understanding of a task or environment or user, is a crucial component of all medical and health-care robots. In image-guided surgery, image data must be analyzed and transformed into useful information about particular features, such as organs, obstacles, and target. Another form of perception relevant to health care is interpreting tactile, force, and contact sensor data to build models of humans, robots, and environments, and the interaction between them. Finally, a key challenge for systems that interact with a user is real-time perception and understanding of the user's activity to enable effective human–machine interaction. Natural, unconstrained human behavior is complex, notoriously unpredictable, and fraught with uncertainty.

Robust, High-Fidelity Sensors

Sensors, along with perception algorithms, are often necessary to give the state of a caregiver/physician, the patient, and (in some cases) the environment. Biocompatible/implantable sensors would be a great catalyst to major advancements in this field. The close physical interaction between robots and patients requires systems that will not harm biological tissues or cease to function when in contact with them. When robots work in unstructured environments, especially around and in contact with humans, using the sense of touch is crucial to accurate, efficient, and safe operations. Tactile, force, and contact data are required for informed manipulation of soft materials, from human organs to blankets and other objects in the household. Current sensors are limited in robustness, resolution, deformability, and size.

Novel Mechanisms and High-Performance Actuators

For systems ranging from ultraminimally invasive surgery robots to human-size prosthetic fingers, robots need very small actuators and mechanisms with high power-to-weight ratio. These designs will allow us to build robots that are smaller, use less power, and are less costly. In surgery, novel mechanisms are needed to allow dexterity of very small, inexpensive, and sterilizable (or disposable) robots that can be controlled from outside the body. Image-guided surgery relies on robots that eliminate electric and magnetic components. Advanced prostheses motivate the design of highly dexterous robot hands and strong artificial arms and legs that consider the volume and weight constraints demanded by the human form. The power-to-weight ratio of conventional (electromechanical) actuators is inferior to many other potential technologies, such as shape memory/superelastic alloys and direct chemical to mechanical energy conversion.

Learning and Adaptation

As discussed earlier, the ability of a system to improve its performance over time and improve the user's performance is key to medical and health-care robotics. Toward this end, dedicated work is needed in statistical machine learning applied to real-world uncertain and multimodal medical and health data. Such algorithms must ensure guaranteed levels of system performance (safety and stability) while learning new policies, behaviors, and skills. Efforts in the domain of learning and skill acquisition by teaching, demonstration, and imitation need to be directed toward real-world medical and health domains, again using real-world uncertain data for grounding in relevance.

Physical HRI

Such interaction is inherent in most medical applications. Modeling and/or simulation of human form and function are the basis for the design of robots that come into physical contact with humans. Significant work is required in this area, as we do not fully understand models of humans for optimizing systems. In addition, haptic feedback can improve performance in terms of accuracy, efficiency, and comfort.

Socially Assistive HRI

The user's willingness to engage with a socially assistive robot to accept advice, interact, and ultimately alter behavior practices toward the desired improvements rests directly on the robot's ability to obtain the user's trust and sustain the user's interest. User interfaces and input devices that are easy and intuitive for a range of users, including those with special needs, must be developed. Social interaction is inherently bidirectional and thus involves both multimodal perception and communication, including verbal and nonverbal means. Thus, automated behavior detection and classification as well as activity recognition, including user intent, task-specific attention, and failure recognition, are critical enabling components.

Modeling, Simulation, and Analysis

A variety of models are important for medical and health-care robotics applications. We divide these into two main categories: people modeling and engineered systems modeling. The models can be of biomechanics, physiology, dynamics, environment, geometry, state, interactions, tasks, cognition, and behavior. The models can be used for many tasks, including optimal design, planning, control, task execution, testing and validation, diagnosis and prognosis, training, and social and cognitive interactions.

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