Lending a Helping Hand

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Toward Novel Assistive Robotic Arms

Assistive robotics is an increasingly popular research field, which has led to a large number of commercial and noncommercial systems aimed at assisting physically impaired or elderly users in the activities of daily living. In this article, we propose five criteria based on robotic arm usage scenarios and surveys with which assistive robotic arms can be classified. Different possibilities and implementations to obtain each criterion are treated, and examples of current assistive robotic arms are given. Implementations and systems are discussed and rated qualitatively, which leads to the observation that variable stiffness actuation offers great benefits for assistive robotic systems despite an increase in the overall complexity.

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Robotic Arms

People with upper extremity disabilities (e.g., caused by spinal cord injury or multiple sclerosis) find themselves in need of continuous assistance and care. Currently, professional personal care is constantly necessary to perform daily tasks such as personal hygiene, getting dressed, moving objects, eating, and drinking. Complete dependence on caregivers has a tremendous impact on the quality of life. Therefore, the usage of robotic arms to assist physically impaired people becomes increasingly popular. Consequently, robotic arms are used to perform the everyday tasks that the user can no longer perform with his/her own arms. This not only improves independence and general quality of life, but also decreases societal expense [1].

User Demands

Several studies have been done to assess and gain insight into possible usage scenarios of potential robotic arm users. Four predevelopment and five postdevelopment surveys on

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the usage of assistive robotic arms are reviewed in [2], where it is concluded that users give the highest task priority to picking up objects from the floor or shelves and carrying them. Moderate or high priority is given to eating/drinking, preparing food/drinks, performing personal hygiene, and enjoying leisure and recreational activities. Since leisure and recreational activities are user-specific, assistive devices should be able to assist in a broad range of tasks. This creates the need for a mobile device instead of a fixed workstation, capable of functioning in a variety of unstructured environments. In [3], through a user and caregiver survey over a six-month period, 12 desirable tasks for robotic arms are found that can be classified into five groups according to the previous prioritized tasks: eating/drinking, personal hygiene (e.g., shaving, bathing), picking up/manipulating objects, personal mobility (e.g., opening doors, operating switches), and leisure/work (e.g., playing games, changing CDs).

The reviewed surveys seem to agree that, generally, users want to be able to perform the activities of daily living with assistive robotic arms in highly unstructured environments, which provides them with greater independence and mobility. The majority of potential users state they would consider adopting such assistive devices [4], [5].

A user should be able to control a robotic arm easily with a proper interface, so considerable research effort is put into finding the suitable solutions. However, in this article, we do not focus on the requirements of the assistive robotic arms from a user's perspective but on the properties of the arm itself that are beneficial in its assistive usage instead. Although prior work has been done to show trends in the development and evaluation of assistive robotics [6], an assessment based on mechanical arm properties is not yet presented in the literature.

Robotic Arm Usage Demands

A high level of human-robot interaction is required when an assistive robotic arm is used, for instance, for the eating/drinking or personal hygiene tasks. Safe behavior is the most important feature during such interaction in nominal situations, but this safety should also be guaranteed in case of accidental arm collisions with the environment. Besides safety, when objects are manipulated/picked up, and in case of an autonomous operation, a proper position control of the arm by the user is required. In general, since there is a need for a mobile assistive system instead of one that is fixed at a workplace, the energy consumption of such assistive systems becomes increasingly important. Proper design considerations and high-efficiency electronics contribute to a reduction of the energy consumption, but being able to store externally injected energy, e.g., upon impacts, and being able to shape the intrinsic dynamics can also considerably reduce energy consumption. Assistive robotic arms are used in highly unstructured environments for fulfilling a broad range of tasks, therefore, demands on safety and the performance vary. The capability of adapting to these demands provides the usage flexibility and safety. Therefore, a classification and rating of assistive robotic arms can be done according to the following five criteria:

1) *Interaction safety:* associated with the level of the human safety when a human interacts with a robot
2) *Shock robustness:* covers the robustness of the robotic system upon the high-impact shocks
3) *Position control:* accounts for the accurate and the repeatable positioning capabilities
4) *Energy:* associated with storing/reusing impact energy and the dynamics shaping
5) *Adaptability:* describes the adaptability of systems with respect to the dynamic tradeoff between the performance and the safety, which may be necessary under the influence of arbitrary environments and conditions.

Even if this might not be an exhaustive list of criteria for the full classification and rating of the suitability of a robotic system for assistive purposes, these criteria do capture the fundamental properties that are clearly worth analyzing.

Interaction Safety

Assuring the safe behavior of an assistive robotic system is prioritized during its development. Since safe behavior is not directly measurable, several safety criteria have been defined in the literature to assess certain safety properties, e.g., the Gadd severity index, lateral pelvic acceleration, thoracic trauma index, and possibly the most well-known and widely used, head injury criterion (HIC) [7]. The HIC takes a blunt impact to the head into account, measuring head acceleration and quantifying the chances of a severe head injury. The head is a person's most critical part and indeed a severe injury can be disastrous. However, cuts and bruises are not taken into account, but can still be very serious. Therefore, in [8], a safety norm is introduced that quantifies the intrinsic safety of an arm, which holds even when a part of the (control) system fails. More recently, a draft of the ISO 13482 standard [9] has been released, aiming to standardize personal care safety and the related risks and hazards (i.e., charging of batteries, incorrect autonomous robot actions, singularity protection, speed and force restrictions, and control) [9]. Since quantification of all the current robotic arms in terms of these safety criteria is beyond the scope of this article, we adopt here a qualitative definition of the interaction safety by stating that a better interaction safety is achieved if a system's measures or properties limit the forces that might be applied to a human and may cause physical injury of any kind during human-robot interaction.

A high level of human-robot interaction is required when an assistive robotic arm is used.

The interaction safety of robotic arms is a measure for the suitability of human-robot interaction and is associated with the intrinsic and extrinsic, i.e., the passive and active, safety measures. The intrinsic safety measures refer to measures that increase the safety even when no power is supplied to the system, while the extrinsic safety measures refer to the safety measures that rely on external power. Possibilities for achieving interaction safety that have been shown in the literature include limiting an arm's performance, incorporating joint backdrivability, using an active impedance control, and implementing intrinsically compliant joints.

Incorporating mechanical or electrical constraints in the system can lead to a higher level of safety. If, for instance, the maximum speed and force of the arm are kept low and the arm collides with a human, there is little chance of injury. Such constraints on the mechanical or the electrical characteristics are defined here as the performance limits. Limiting the performance of a robotic arm can be done by, for instance, limiting the arm's movement speed and acceleration in space, the end-effector force, and the maximum possible payload. The speed limits in combination with low arm inertia ensure that the momentum with which a human is accidentally hit is kept low. Examples of such systems are JACO [10] and iARM [11]. Contrary to the current limits that can be changed on demand, using low-power motors is a way of statically and intrinsically limiting an arm's acceleration, force, and payload, as done in Weston [12]. Also, Bridgit [13] and RAPUDA [14] are systems that limit their performance to increase safety. The iARM is also an example of a system that incorporates slip clutches, i.e., mechanical power transmission couplings between the actuator and the joint. They disconnect or slip the transmission when the applied joint torque exceeds a certain maximum, thus limiting the end-effector payload and the possible force on the environment [15].

The position control is very effectively used and optimized in industrial applications.

Using backdrivable joints is another way of increasing safety. Backdrivable joints do not resist an external output motion, depending on the amount of current supplied to (and therefore torque supplied by) the joint motors. Therefore, a user is able to manipulate the system externally without feeling a rigid arm structure. Examples of systems using backdrivable joints are JACO and WAM Arm [16].

The active impedance control [17], often applied to intrinsically stiff joints that have a stiff coupling between an actuator and joint, is a well-known strategy of incorporating a means of safety in a robotic system. As opposed to the position control where the error between a desired and actual position has to be minimized, the impedance control regulates the interaction between an end-effector and its environment. This way, a virtual compliance can be included at the joint level between the motor and the output, causing the human operator to perceive a softer arm. Because of this soft behavior, the arm becomes safer to use. Examples of systems that use this type of control are KARES II, WAM Arm, Elumotion RT2 [18], DLR LWR-III [19], Modular Prosthetic Limb [20], and DLR HASy [21].

In intrinsically compliant joints, compliance or stiffness during the interaction between the end-effector and the environment is realized by a physical elastic element, e.g., a mechanical spring which is put between the actuator and the joint, as opposed to a virtual elastic element in the case of active impedance control. The stiffness felt during interaction is physical stiffness due to the elastic element. Therefore, these joints are intrinsically safe during interaction, since they do not rely on limited bandwidth controllers or possibly unreliable measurements. An example of such a system is Robonaut 2 [22], which uses a series of elastic joints to actuate the arm. Much like the active impedance control, which mimics elastic elements of varying compliance, variable compliant joints or variable stiffness joints [23] can adjust their physical stiffness between the actuator and the joint. In this type of joint, at least two motors are used to simultaneously control position and the stiffness. Examples of such systems are DLR HASy and MIA Arm [24]. Although the active impedance control can still be applied to intrinsically compliant joints, safe interaction behavior is guaranteed by the design.

Shock Robustness

Shock robustness is a criterion for estimating the amount of damage an arm suffers upon external high-impact shocks. Arm joints are the most sensitive to these shocks and therefore should be protected. Shock robustness can be achieved by using a system bandwidth capable of absorbing the shocks or by allowing the temporary mechanical decoupling of the actuator from the joint. Both measures can prevent damage to the motors and gearboxes upon the shocks.

A system bandwidth capable of reacting to the arbitrary shocks can be realized only physically, i.e., by using the intrinsically compliant joints. Again, these joints contain a physical elastic element between the actuator and joint, thereby converting kinetic impact energy to potential energy, as in DLR HASy, Robonaut 2, and MIA Arm.

The mechanical decoupling of the actuator from the joint upon high impacts prevents damage to the motors and gearboxes. This can be achieved by using the joint slip clutches, which decouple the power transmission, thereby allowing the joint to move passively and allowing the conversion of kinetic impact energy to kinetic energy in the decoupled arm. Also, the backdrivable direct-drive joints, i.e., the joints without nonbackdrivable gearboxes, ensure that no damage occurs since the kinetic impact energy does not have to be absorbed by the gearbox, motor, or arm structure. Examples of systems with slip clutches or backdrivable joints are JACO, iARM, and WAM Arm.

Position Control

Besides safe interaction, maintaining accurate position control is also important to assistive robotics for object grasping, manipulation, and autonomy. Position control is very effectively used and optimized in industrial applications, e.g., in the automobile industry. Typically, these robots have highly stiff structures driven by stiff joints, and their eigenfrequencies are implicitly high; so, the control bandwidth can be large. For a fast position control, a lower mass allowing higher accelerations is beneficial, but it increases the disturbance sensitivity of the system and puts higher requirements on control. Therefore, system mass is often a tradeoff among the required speed, available power, and control constraints. High-resolution joint encoders provide accurate feedback, and therefore, repeatability.

Examples of systems that ensure an accurate position control and repeatability by stiff structures/joints and high-resolution joint encoders are [3], [10]–[14], [16], [18]–[20], and [25]–[29].

Energy

The energy criterion relates to the capability of storing energy and reusing it at a later stage and the possibility of using and shaping intrinsic system dynamics to achieve a desirable motion with little actuation, which is energetically efficient. Being energy efficient is an important feature, since assistive robotics are preferably mobile, and therefore should be able to operate independently from an external power source for a considerable amount of time.

Storing energy can only be done by incorporating a physical storage element, like a mechanical mass or spring, or an analog element in an arbitrary domain, e.g., an electrical inductor or a capacitor. A moving mechanical mass stores kinetic energy, so if the kinetic energy at the load of a robotic arm is transferred to this mass, the energy can be stored and reused later (e.g., regenerative braking). Since storing much energy in this way requires a large mass and high speed, a mechanical elastic element may be used instead. The kinetic energy is then stored as potential energy by, for instance, using the mechanical springs. Examples of systems that have the capability to store energy using mechanical springs are DLR HASy, Robonaut 2, and MIA Arm.

Useful intrinsic system dynamics are any dynamics that require no additional external energy that can contribute to a certain desired motion or behavior, and are most often oscillatory of nature. Adjustment of these intrinsic dynamics offers flexibility in achieving energy-efficient motion, i.e., a desired motion that is primarily the consequence of intrinsic dynamics as opposed to actuation. The MIA Arm and the DLR HASy can tune intrinsic system dynamics by tuning their joint stiffness and, thereby, possibly adjusting useful resonance frequencies.

Adaptability

The adaptability criterion of an assistive robotic system relates to its ability to change system properties to provide a *dynamic* tradeoff between safety and performance. This means that, for instance, safety can be decreased if more performance is needed (e.g., a higher speed has to be reached), which may be necessary due to unknown arbitrary environments and conditions. Just like interaction safety, adaptability can be achieved by either active measures, e.g., shaping the performance limits and using the active impedance control, or by passive measures e.g., variable stiffness joints.

Adjusting motor current limits to reduce the maximum possible force that can be applied by the joints (and therefore the arm's end-effector), or adjusting the speed and acceleration limits increases safety by reducing the possible force with which a human may be hit. An example of a system that uses adjustable performance (speed) limits is iARM.

The active impedance control allows the force that is applied to a load to be controlled. Since this is done actively, e.g., in software, the virtual elastic element can be tuned to a desired value required for safety, performance, or other conditions. Examples of systems that have shown ability to adapt the safety and performance tradeoff by means of active impedance controls are KARES II, WAM Arm, Elumotion RT2, DLR LWR-III, and Modular Prosthetic Limb.

The variable stiffness joints can adapt the physical stiffness perceived at the output side of a joint. Decreasing this physical stiffness means the joint is perceived as a softer spring, while increasing stiffness means that the joint is perceived as a stiffer spring. The former implies an intrinsic increase in the safety and probable degradation of the performance, whereas the latter implies an intrinsic decrease in the safety but an improved performance. Examples of systems with variable stiffness joints are DLR HASy and MIA Arm.

Discussion

Based on usage surveys, general usage scenarios have been reported in the section on the robotic arms. From these preferences, we have proposed five criteria to evaluate the assistive robotic arms. Several possible implementations to meet the five criteria are discussed in the previous sections and examples of current assistive robotic systems are given that reflect these implementations. Some of the criteria are not completely independent and are related or coupled with another criterion. The energy criterion, for instance, is related to interaction safety and shock robustness if the energy-storing capabilities are achieved by implementing a physical elastic element, interaction safety is achieved by robust force control, and shock robustness is achieved by the capability to store kinetic impact energy as potential energy in the elastic element. However, the reverse does not necessarily hold; if shock robustness is provided by slip clutches, no energy-storing capabilities are implicitly provided. The same holds for adaptability and interaction safety; a suitable system adaptability, according to the criterion, means good interaction safety as a consequence, but suitable interaction safety may be achieved by static implementations (for instance, by using the low-power motors), which results in low adaptability.

Table 1: Comparison of the assistive robotic systems mentioned in this article. The comparison is based on function and utilization, mechanical properties, performance and safety and robustness, and only information as provided in published literature is used. A property is marked "n/a" if it is not applicable, not assignable or not specified, "–" if it is absent, or rated unsuitable, "+/–" if it is rated fair and "+" if it is rated suitable.

	iARM (11)	JACO (10)	Weston (12)	RAPUDA (14)	KARES II (3)	FRIEND (26)	Elumotion RT2 (18)	DLR LWR-III (19)	Boston Digital Arm (28)	Modular Prosthetic Limb (20)	WAM Arm (16)	Robonaut 2 (22)	MIA Arm (24)	DLR HASy (21)	Raptor (30)	Bridgit (13)	USF WMRA-II (25)	Asimov (27)	DEKA Arm (29)
Function and Utilization																			
Type[1]	WMRA	WMRA	WMRA	WMRA	WMRA	WMRA	General purpose	General purpose	Prosthesis	Prosthesis	General purpose	Human-like robotic austronaut	Human-like robotic arm	Human-like robotic arm	WMRA	WMRA	WMRA	WMRA	Prosthesis
Tasks[2]	ADL	ADL	ADL	ADL	ADL & APL	ADL & APL	Human-robot interaction platform	General purpose	ADL for amputees	ADL for amputees	General purpose	Cleaning, maintenance, repair	General human-like arm behavior	Human activities	ADL	ADL	ADL	ADL	ADL for amputees
Interface	(wheelchair) joystick, keyboard, one-button interface	Computer, 3-axis 7-button joystick interface	2 DOF joystick interface (hand or chin)	Joystick	Eye-mouse, EMG, haptic suit (head/shoulder)	Chin or hand joystick, speech, eye-control, brain-computer interface	n/a	n/a	Myoelectrodes, touch pads, servo controls, or switches	Thought controlled	n/a	n/a	n/a	n/a	Ten-button controller or eight-position joystick	Three little joysticks and three buttons	Computer	Wheelchair joystick	Nerves, muscles or foot pedals
Arm Mechanics																			
DOFs[3]	6	6	6	6	6	7	7	7	1	4[6]	7	7	7	7	7	4	5	7	7
Configuration[4]	R-P-P-R-P-R	R-P-P-R-R/P-R	T-P-P-P-RP	R-P-T-R-PP	R-P-P-R-PR	R-P-R-P-R-P-R	R-P-R-P-R-PP	R-P-R-P-R-PP	P	R-P-R-P-R-PP	R-P-R-P-R-P-R	R-P-R-P-R-PP	R-P-R-P-R-PP	R-P-R-P-R-PP	P-R-P-R	R-P-P-P-R	R-P-R-P-R-P-R	n/a	P-R-P-R
Actuation	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff	Stiff, direct drive	Series elastic	Variable stiffness	Variable stiffness	Stiff	Stiff	Stiff	Stiff	Stiff
Mass (kg)	8.9	5	n/a	6	n/a	10.6	n/a	1/4	n/a	4.5	27 incl. base	n/a	25	n/a	n/a	4.5	11	13	4.5
Reach (m)	0.9	0.9	0.8 (circle), 0.3 × 0.4 (rectangle)	≈1	n/a	1.87 × 1.65 × 1.87	≈1	0.936	≈0.4	≈1	1	0.8	0.55	≈0.7	1.2	0.65	1.12	1.5	≈1
Performance																			
Payload at max. extension (kg)	1.5	1	n/a	0.5	n/a	1.5	n/a	14	4.5	n/a	3	> 10	n/a	n/a	2	0.5	3.85	1	n/a

Max. end-effector speed (m/s)	0.15	0.15	“slow”	”slow”	n/a	n/a	n/a	n/a	n/a	n/a	3	2	1	n/a	n/a	n/a	n/a	n/a	n/a
Max. joint speed (rad/s)	0.7	0.84	n/a	n/a	n/a	n/a	3.05	2.1	1.75	n/a	n/a	n/a	1.88	10.5	n/a	n/a	n/a	6.28	n/a
Safety and Robustness[5]																			
Intrinsic	Slip clutches, low arm inertia due to motor placement, compliant gripper	Back-drivable joints, low arm inertia due to carbon fibre	Grip force maintained on power loss	–	–	–	–	–	–	–	Back-drivable joints	Constant stiffness joint	Variable stiffness joint	Variable stiffness joint	n/a	–	–	6.28	n/a
Extrinsic	Adjustable speeds, limited accelerations, limited gripper force	Redundant security and error checking in joints and control, limited gripper force	Low power motors	Redundant sensor system	Active impedance control	Permanent magnet brakes on joints	Limit switches, active torque control	Active impedance control, joint brakes	–	Active impedance control	Robust force-control due to direct drive, independent of force/torque sensors	Electromagnetic failsafe brakes, force/torque sensors besides force measurement via series elastic	n/a	Active impedance control to extend the reachable actuator workspace	n/a	n/a	n/a	6.28	n/a
Qualitative Rating																			
Interaction safety	+	+/–	+	+	+/–	–	+/–	+/–	–	+/–	+/–	+	+	+	n/a	n/a	n/a	n/a	n/a
Shock robustness	+	+	–	–	–	–	–	–	–	–	+	+	+	+	n/a	–	–	n/a	–
Position control	+	+	+	+	+	+	+	+	+	+	+	+/–	+/–	+/–	–	+	+	n/a	+
Energy	–	–	–	–	–	–	–	–	–	–	–	+/–	+	+	–	–	–	–	–
Adaptability	–	–	–	–	+/–	–	+/–	+/–	–	+/–	+/–	+/–	+	+	–	–	–	–	–

[1] “WMRA” refers to wheelchair mounted robotic arms.

[2] “ADL” refers to activities of daily living, “things that people normally do.” “APL” refers to activities in professional life.

[3] The degrees of freedom (DOFs) are only the degrees of freedom of the arm, without any optional lifts, rails, or the end-effector.

[4] The joint configuration is represented by roll (R), pitch (P), and prismatic (T).

[5] “Intrinsic” refers to system properties while the system is not powered. “Extrinsic” refers to additional system properties while the system is powered.

[6] In case of above-elbow amputees. In general, any number of DOFs is possible since it is a modular system.

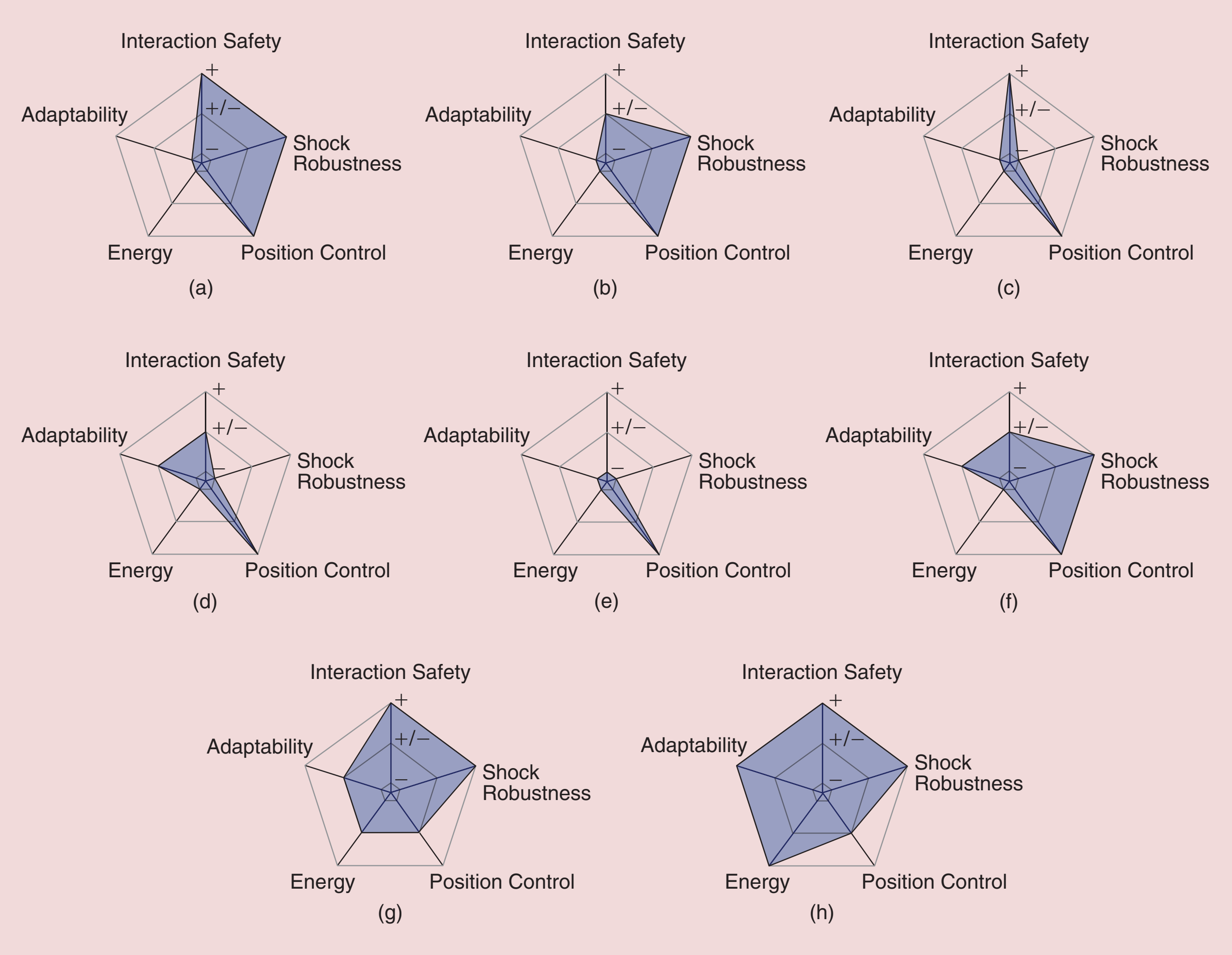

Figure 1. The radar plots of assistive robotic arms mentioned in this article, comparing five criteria along the five axes. It can be seen that devices with variable stiffness joints have the best overall rating (the largest shaded area) for these five proposed criteria. This includes MIA Arm and DLR HASy. (a) iARM, (b) JACO, (c) Weston, RAPUDA, (d) KARES II, Elumotion RT2, DLR LWR-III, Modular Prosthetic Limb, (e) FRIEND, Boston Digital Arm, (f) WAM Arm, (g) Robonaut 2, and (h) MIA Arm, DLR HASy.

The mentioned robotic arms are organized in Table 1, where their functions and utilizations are treated, arm mechanics and performance are given, and the safety and robustness properties are summarized. Since not every implementation for obtaining one of the criteria is as suitable as another, this section discusses these possibilities and rates their suitability toward the criteria in a qualitative way, as shown in the bottom rows of Table 1 and in the plots of Figure 1. A system is rated "−" if it is unsuitable, "+/ −" if it is fair or adequate, and "+" if it is suitable.

Interaction Safety

Three implementations to increase interaction safety are found in the current assistive robotic systems, i.e., limiting the arm's performance, incorporating the backdrivability, using the active impedance control, and incorporating the intrinsically compliant joints.

Intrinsic safety is achieved if the measure for obtaining the safety is perceived when the system is not powered, as opposed to extrinsic safety in which that measure is actively controlled by a control system relying on possibly unreliable measurements. Therefore, the former has the greater level of safety, since it is independent of crucial measurements and control systems. If no deliberate performance limits are chosen on a stiff robotic arm, it is unsafe for interaction. FRIEND [26] does not have the safety measures apart from permanent magnet brakes and is, thus, rated "−." The performance limits are intrinsically safe if the low-power motors are used that are under no circumstance capable of inducing too high loads. Also, slip clutches limit the maximum applicable joint torque and end-effector payload, which increases the intrinsic safety. Hence, iARM and Weston are rated "+." The speed or current limits increase the safety, but are dependent on accurate measurements. RAPUDA was targeted at the safety regarding certifications and has a redundant sensor system, increasing the reliability of the measurements. Since its speed and payload performance are limited as well, it is also rated "+."

Stiff joints can be given backdrivability, which allows the external positioning of a joint. Since it depends on the amount of current in (and, thus, applied torque by) the joint motor, which can be high, safety cannot be guaranteed. Hence, JACO and WAM Arm are rated "+/ −."

In addition to stiff joints, the active impedance control might suffice with respect to safety in nominal conditions during gentle interaction and without sudden disturbances. However, because of their limited bandwidth due to data processing in a digital control loop and actuator limitations, the intrinsic rigid structure of joints is felt upon a sudden disturbance and even instability may occur. Thus, active impedance cannot guarantee safety in situations where a human has to constantly interact with the robot. Therefore, KARES II, Elumotion RT2, DLR LWR-III, Modular Prosthetic Limb, and WAM Arm are rated "+/ −." A need for intrinsic safety arises, which can be achieved by passive compliance like the series elastic and variable stiffness joints, i.e., DLR HASy, Robonaut 2, and MIA Arm. These systems have an intrinsic interaction safety, i.e., a physical elastic element independent of external power and control bandwidth limitations, and are, thus, qualitatively rated "+."

Shock Robustness

Shock robustness is treated as a measure for the amount of damage an arm suffers upon the external high-impact shocks. The slip clutches that decouple the actuators from the joint at too high torque prevent damage to the motors and gearboxes. Also, ensuring the backdrivability of joints such that the arm is free to be moved externally prevents damage. Therefore, iARM, JACO, and WAM Arm are rated "+."

Since a control system can mimic an elastic element by the active impedance control, the motors and gearboxes can be protected from these shocks. However, even when the active impedance control is applied, a stiff robot is damaged at a sudden severe shock, since its bandwidth is never large enough for the arbitrary shocks. Passive elastic mechanisms are robust against the shocks, since their physical elastic element has an infinite disturbance bandwidth and ensures that the impact energy is not absorbed by the mechanical structure but is converted to the potential energy. Therefore, Robonaut 2, MIA Arm, and DLR HASy are rated "+." The rest of the systems in Table 1 are rated "–," since their joints are stiff and must absorb impact energy in their structure, most likely resulting in considerable damage.

Position Control

As mentioned in the section "Position Control," the well-designed stiff robotic arms with high-resolution joint encoders are the best choice for accurate positioning tasks and good repeatability, as shown in industrial environments. Only high-frequency dynamics are present, which means that a large control bandwidth, and therefore a fast and accurate position control, is possible. In short, and for this reason, all systems that are actuated by the stiff joints are rated "+." Their structural stiffness could not be assessed but was assumed not to be a limiting factor for a proper position control. In case of the absence of joint encoders, an arm has no autonomous positioning capabilities, of which, the Raptor [30] is an example and therefore rated "–."

Adding compliance to a stiff system means lowering the system's eigenfrequencies, which may cause considerable oscillatory dynamics and degraded positioning performance. The variable stiffness joints can stiffen their compliance, thereby acting as the stiff joints with good accuracy and repeatability when needed. Although the position control of a soft arm was shown in [31], it is more challenging as opposed to stiff joint control, since the weakly damped elastic joints exhibit a considerable oscillatory behavior that should be damped to obtain an accurate position control. Therefore, Robonaut 2, MIA Arm, and DLR HASy are rated "+/ −."

Energy

The energy criterion treats the capability of storing the energy from impacts and reusing it at a later stage and the possibilities for using and shaping the intrinsic system dynamics to yield the energy-efficient motions.

Stiff systems have no considerable usable intrinsic dynamics apart from small oscillatory behavior, due to finite structural stiffness and nonzero mass. Moreover, no system properties can be varied to yield varying intrinsic dynamics and, as no storage element is present, no energy can be stored. These systems are not suitable for energy efficiency, so all systems actuated by stiff joints are rated "–."

The series elastic actuation has the ability to store and reuse the (impact) energy by converting the kinetic energy to the potential energy by compressing a mechanical spring. However, since this type of joint has one physical spring and therefore a fixed compliance, its dynamics are determined. Hence, Robonaut 2 is rated "+/ −." Only the variable stiffness joints can store impact energy and simultaneously adjust their joint dynamics to achieve behavior that is close to a desired motion. Moreover, the energetic benefit with respect to a constant stiffness joint outweighs the additional energy consumption of an additional stiffness changing motor [32]–[34]. Hence, DLR HASy and MIA Arm are rated "+."

Adaptability

Adaptability covers the ability of a system to change properties to obtain a dynamic tradeoff between the safety and performance. This tradeoff may be necessary for varying usage requirements and unknown environments or conditions.

The performance-limiting measures are used in various systems, e.g., limiting the payload and the movement speed, to ensure a certain level of safety. Also the slip clutches are used to limit the maximum possible joint torque, which increases the intrinsic safety. However, these limitations yield a serious static tradeoff between the performance on one side and the human-robot interaction safety on the other side, since these are measures that may not be suitable for all situations. The adaptability of such systems, e.g., more performance at the cost of safety, is therefore insufficient [10]–[14], [25]–[30].

The active impedance-controlled devices can trade off safety and performance by mimicking a stiffer or more compliant spring. However, since this is not intrinsically safe and it relies on accurate measurements and a proper control bandwidth, the KARES II, DLR LWR-III, DEKA Arm, Modular Prosthetic Limb, Elumotion RT2, and WAM Arm are rated "+/ −." Despite a physical elastic element in the joints of Robonaut 2, the safety and performance adaptability relies on the active impedance control and is, thus, also rated "+/ −."

In case of the variable stiffness joints, this tradeoff can be dynamically adjusted by tuning the internal stiffness, i.e., decreasing the stiffness for increased intrinsic safety and increasing the stiffness for increased payload performance and accuracy. Thus, MIA Arm and DLR HASy are rated "+."

The Drawbacks: Complexity, Reliability, and Cost

Although systems may be designed in a complex way such that the discussed criteria are met, the result might be a system that is not suitable for assistive purposes due to its level of complexity. The fundamental concern of increased complexity is the consequence on the reliability. The more complex a system is designed, e.g., to achieve certain desirable properties as described in the previous sections, the higher the probability of failure and the less reliable it becomes. Keeping the systems as simple as possible very often ensures better reliability. Another concern of complexity is the maintenance cost that might increase for complex (mechanical) solutions.

All individual systems cannot be rated toward complexity and reliability without testing the systems for endurance, and therefore complexity is not proposed as a criterion. However, some aspects can be discussed, of which joint actuation implementation is the most obvious. A stiff joint, coupling the actuator rigidly to the moving joint, has been successfully applied for decades because of its low complexity and high reliability, partly as a consequence of few components. Therefore, it is also the most inexpensive solution to build as well as to maintain. These types of joints are not intrinsically safe, and very often the active impedance control is applied. The flexibility of this strategy is unsurpassed, since this control can be completely done in software and adapted very easily. However, since this method relies on accurate end-effector position measurements, safety cannot be guaranteed. A constant stiffness joint, e.g., series elastic actuation, adds a physical elastic element and possible mechanical transmission to the joint actuator that introduces more mechanical components and, thereby, increases complexity and, probably, maintenance cost. Moreover, by adding the elastic element, a new resonance frequency is introduced, which might make the stabilization of the system more difficult. The active impedance control can still be applied, such that one gains from the intrinsic safety of a physical elastic element (albeit dependent on the particular elastic element) and the flexibility of controlling the impedance in software. Realizing a joint with variable stiffness is more complex, since complex mechanical structures with many components are generally required to obtain the variable nature of the actuator output stiffness, adding even more to build and maintenance cost. Likewise, variable compliance in the robotic joint adds a variable resonance frequency and, again, might make the system stabilization more difficult. However, one does obtain unconditional intrinsic safety along with the flexibility of being able to adapt the physical joint stiffness by control.

Implementations to obtain, for instance, increased safety and shock robustness (e.g., slip clutches) might also increase the complexity and wear of the system, thereby possibly decreasing its reliability. However, giving a general rating of each implementation is not possible, since the precise effects on the complexity and the long-term reliability are unknown.

Observations

In Figure 1, radar plots of the assistive robotics arms mentioned in this article are shown. These plots give a graphical indication of the suitability of each system toward the proposed criteria. Obviously, the larger the shaded area is, the better the system scores with respect to the five criteria. Note that the systems that could not be rated completely are omitted. These ratings are also summarized in Table 1, along with system features and performance numbers.

It is observed that all systems score adequate or well at one or two of the criteria that were proposed in this article. It can be seen that the systems that do not score well overall are actuated by the traditional stiff joints, with exceptions being iARM, JACO, and WAM Arm. Their interaction safety, shock robustness, and position control are adequate or good, but lack the energy-storing capabilities and proper adaptability of safety measures to increase performance in situations where safety is less important. An improvement is the series elastic actuation in Robonaut 2, which has increased safety and allows storage of energy at a small cost of the position control. It is observed that MIA Arm and DLR HASy have the best rating over all five criteria with the exception of position control, which is more challenging for weakly damped compliant systems than stiff systems. Hence, it seems that constant stiffness joints improve on stiff joints with respect to the interaction safety and energetic properties, and variable stiffness joints improve on this further with respect to the energetic properties and the adaptability.

The assistive robotic arms of the future demand good ratings in all five criteria. This applies to arms like the Robonaut 2, MIA Arm, and DLR HASy, and ultimately the latter two, since the variable stiffness joints have advantages over constant stiffness joints regarding energy and adaptability. These actuators offer the highest level of intrinsic safety of the systems that were treated because of the soft arm behavior even when the system is not powered. A good shock robustness and the capability of storing impact energy are achieved by using a physical elastic element. Since the compliance of this element can be adjusted, intrinsic dynamics shaping is possible and the adaptability of the arm's safety can be traded off with its performance, allowing versatile usage. However, these systems' drawbacks are the complexity and, thus, possibly limited reliability and increased (maintenance) costs. Despite this, it is observed that the variable stiffness joints offer great benefits for assistive robotics.

Conclusion

In this article, we highlighted the potentials of using variable stiffness joints for assistive robotic devices and, in particular, arms. This observation is motivated by evaluating current assistive robotic systems on five criteria, which were based on usage surveys. These surveys indicate that eating/drinking and picking up/manipulating objects are high-priority tasks that demand a high level of interaction. The properties of the current assistive robotic platforms were qualitatively rated against the proposed criteria. Most current platforms score well at two criteria, but do not score well at others. Only the variable stiffness joints ensure a suitable rating for all criteria and offer great benefits for the assistive robotics, despite the increased overall complexity.

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