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Lock your robot

Plooij, Michiel; Mathijssen, Glenn; Cherelle, Pierre; Lefeber, Dirk; Vanderborght, Bram

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Review of locking devices used in robotics

Michiel Plooij*, Glenn Mathijssen†, Pierre Cherelle†, Dirk Lefeber† and Bram Vanderborght†

***Abstract*—Locking devices are widely used in robotics, for instance to lock springs, joints or to reconfigure robots. This review paper classifies the locking devices currently described in literature and preforms a comparative study. Designers can, as such, better determine which locking device best matches the needs of their application. The locking devices are divided into three main categories based on different locking principles: mechanical locking, friction-based locking and singularity locking. Different lockers in each category can be passive lockers or active lockers. Based on an elaborate literature study, the paper summarizes the findings by comparing different locking devices, based on a set of properties of a theoretical ideal locking device.**

I. Introduction

There are numerous applications in robotics that use locking devices. Although the reason for using such devices differ per application, there are two main reasons: energy management and reconfiguration.

The first and most often mentioned reason for using locking devices is the energy management in robots. Especially in the field of mobile robots, the energy consumption is an important performance criterion. Examples include household robots [1], legged robots [2] and aerial robots [3, 4]. But also in wearable devices such as prosthesis [5, 6] and exoskeletons [7, 8] the energy consumption is critical. Over the years, the field of robotics has evolved from using stiff actuation to exploiting springs in series and in parallel with the actuator [9]. The advantage of using spings is that they provide the possibility of storing and releasing energy mechanically, which can lower the energy consumption of the actuator [10]. The disadvantage however is that they are non-controllable energy buffers. In order to solve this, two solutions have been proposed to control the energy release of springs. The first solution is to use a continuously variable transmission (CVT) to adjust the position-torque relation of the spring [11]. However, those CVTs are still not developed well enough to be widely applied in robots. The second solution is to use locking devices to control the timing of the energy release. Such locking devices are discussed in this paper.

The second mentioned reason for using locking devices is to change the configuration of the robots. Such robots consist of multiple modules that can be connected and disconnected to form different configurations that perform different tasks. Those modules are connected and disconnected using locking devices of various types [12, 13, 14].

There are multiple locking devices in literature, which are also described in different books like [15, 16, 17, 18, 19]. The principles of locking mechanisms are sometimes already very old, however the importance of the locking mechanisms is raising. Almost half of the citations on locking mechanisms are describing mechanisms that were implemented from 2010. Therefore, this paper discusses the potential of them in robotic applications.

All locking devices have their own properties and none of the locking devices in literature fulfills all the requirements of a perfect locking device. On the other hand, not every application requires a locking device that fulfills all the requirements. Therefore, this paper provides and overview of all locking devices usefull for robotic applications and discusses their properties, advantages and disadvantages, starting with the description of an ideal locking device.

II. Locking devices

A. What is an ideal locking device?

A locking device is a device that switches between allowing and preventing relative motion between two parts. The requirements on a locking device differ per application, but this section lists all the requirements one might have on a locking device. In the rest of the paper locking devices are evaluated on all these requirements, such that the reader will be able to select the most suitable locking device for the application. An ideal locking device has the following properties (in random order):

- **Adjustable locking directions.** Some devices lock in only one direction, others are bi-directional. An ideal locking device can switch between locking in zero, one or two directions.
- **Unlocking while under load.** While there is a force on the locking device, it should still be able to unlock.
- **Low energy consumption.** While the device is (un)locked or while it is (un)locking, it should not consume energy.
- **Lockable in any position.** Some devices have a finite number of locking positions. An ideal locking device has an infinite amount of locking positions.
- **Compact.** The device should be small relative to its application.
- **Lightweight.** The device should be lightweight relative to its application.
- **Short switching time.** Some devices require some time to switch between the locked and unlocked state. An ideal device switches instantaneously.

* Michiel Plooij is with the Delft University of Technology and is funded by the Dutch Technology Foundation STW, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO). Email: m.c.plooij@tudelft.nl

† Glenn Mathijssen, Pierre Cherelle, Dirk Lefeber and Bram Vanderborght are with the Vrije Universiteit Brussel. This work was partially funded by the European Commission ERC Starting grant SPEAR (no.337596).

- **Inexpensive** Since the locker should also be applicable for low cost applications, the device should be inexpensive compared to its application.
- **High locking force.** Ideally, there should be no limit on the amount of locking torque the device can provide.

Some locking devices can also be used as controllable brakes, meaning that the locking torque can be controlled and when the external torque is higher than the locking torque, the brake slips. Although this property is not necessary for a locking device, in some application it might be an advantage and therefore it will be considered as a side note in this paper.

B. Categorization

Numerous locking devices are presented in literature. In this paper, the locking devices are categorized into three main groups, based on three locking principles (see Fig. 1). The three distinguishable categories are:

1) **Mechanical locking:** The position of a mechanical component determines the locking or unlocking. Examples of such components are wedges and pawls. This position can be determined by an actuator or can depend on e.g. the position of a joint or the direction of the velocity. These locking devices are discussed in section III.
2) **Friction-based locking:** Engaging or disengaging two friction surfaces determines if the joint is locked or unlocked. This engagement can be determined by an actuator or can depend on e.g. the position of a joint or the direction of the velocity. These locking devices are discussed in section IV.
3) **Singularity locking:** Singularities in mechanisms cause a transfer ratio to go to infinity. In such a singular position, the locker features an infinitely high locking force and an infinitely small unlocking force. These locking devices are discussed in section V.

Each of these three groups can be subdivided into active locking devices and passive locking devices (see Fig. 1). Contrary to passive locking devices, active locking devices use an actuator to change the timing of the locking, the locking position or the locking torque. Therefore, where passive devices do not require any electronics or control, active devices often use some kind of state machine controller. Section VI compares all the different devices, based on the properties of an ideal locking device described above and section VII provides a guide for the selection of a suitable locking mechanism.

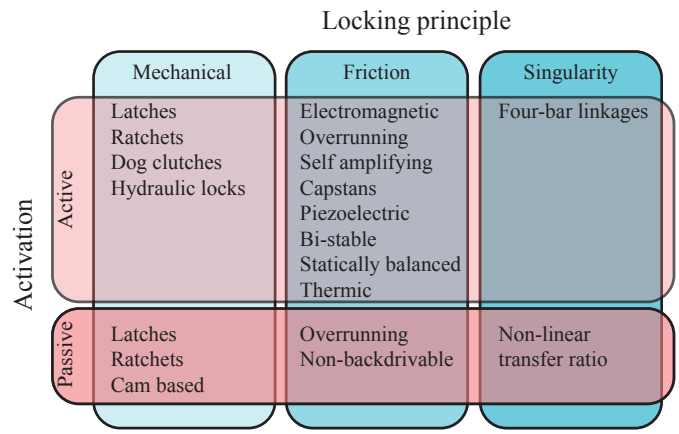

Fig. 1. Classification of the locking devices into three main categories: mechanical locking, friction-based locking and singularity locking. All three can be divided into actuated and passive devices.

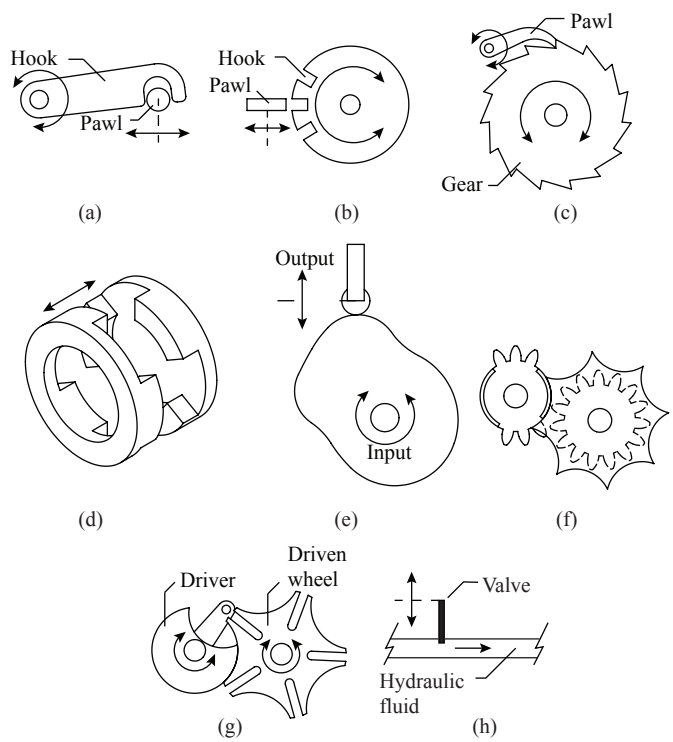

Fig. 2. This figure shows the types of mechanical locking devices with: (a) A latch with one locking position, (b), a latch with multiple locking positions, (c) a ratchet, (d) a dog clutch, (e) a cam-based locker: cam follower, (f) a cam-based locker: mutilated gears, (g) a cam-based locker: geneva mechanism and (h) an hydraulic lock.

III. Locking devices based on mechanical locking

Mechanical locking devices all use some kind of obstruction of a part by another part. For instance, in the latch in Fig. 2a, the hook obstructs the pawl. Sometimes, it is hard to distinguish between mechanical locking and friction based locking devices. The criterion for the categorization in this paper is whether the device also works in a world without friction. If so, it is categorized as a mechanical locking device, if not, as a friction based device. This section describes mechanical locking devices in literature, and indicates which are active lockers or passive lockers.

A. Latches

Latches consist of a pawl and a hook that can generally lock at one position (see Fig. 2a). Active latches use an actuator to change the position of the pawl or the hook for two reasons. Firstly, the positions can be changed to

determine if the hook and pawl obstruct each other at the locking position, and thereby enabling or disabling the latch mechanism. Secondly, the positions can be changed to adjust the locking position itself. Passive latches are latches of which locking and unlocking is caused by the position or velocity of components of the lock. This can be used in robots that have to lock or unlock based on the state of the robot.

Active latches have been used in several walking robots. Firstly, Collins and Kuo [20] used a latch in their energy recycling foot prosthesis to temporarily lock a loaded spring. At the beginning of the push-off phase, the latch was released and the energy returned. Secondly, Wisse et al. [21] used a latch in the knee of the bi-pedal walking robot Denise to lock and unlock the knee joint, depending on the phase of the walking cycle. And thirdly, Karssen [22] used a latch in the knee of the bi-pedal running robot Phides to attach a parallel spring to the knee joint during the stand phase and detach it during the swing phase.

There are other examples of robotic applications that use active latches. Firstly, Tavakoli et al. [23] used a latch to lock two trunks of a flexible gripper. An SMA actuator was used to unlock the latch and disconnect the truncs again. Secondly, Wright et al. [24] used a latch in their snake robot to (un)lock a brake on the segments of the robot. This latch was actuated by an SMA actuator and held in place by a bi-stable spring. And finally, multiple modular robots use latches to join different modules [14]. Latches can also lock at multiple positions, for instance having one pawl and multiple hooks (see Fig. 2b). Such latches have been used by Mitsui et al. [25] in a robotic hand to lock joints in an underactuated finger. While one of the DOF in the fingers is locked the other DOFs are moved by the actuator. This allows the hand to perform different kinds of grasps with a limited amount of actuators, causing the arm to be lightweight and compact.

Unal et al. [26] used passive latches in their ankle-knee prosthesis. Based on the phase of the walking cycle, multiple latches lock and unlock in order to control the energetic coupling between the ankle and the knee during the swing phase and to be able to store energy during the stance phase.

B. Ratchets

A ratchet consists of a round gear or linear rack with teeth, and a pivoting, actuated pawl that engages the teeth and performs the locking (see Fig. 2c). In active ratchets, the pawl is controlled by an actuator that determines engagement or disengagement. There are two possibilities for the loading of the pawl: compression (shown in Fig. 2c) or tension. The pawl of the ratchet mechanism can also be powered by a spring instead of an actuator, making it passive. Such a passive ratchet allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction.

Active ratchets are used in multiple prostheses. Firstly, Geeroms et al. [27] used a ratchet in the weight acceptance mechanism of the knee in an active knee-ankle prosthesis. During the stance phase the knee behaves like a spring, so spring is locked parallel to the knee joint. A disadvantage of this device is that it is difficult to unlock under load, but for this application it is feasible since the ratchet is not highly loaded at the end of the stance phase when it is engaged. Secondly, Brackx et al. [28] used a ratchet mechanism in the ankle prosthesis AMPFoot 1 to change the internal configuration of the foot between loading phase and push-off phase.

A passive ratchet is used by Li et al. [29] in a compressing and releasing energy storage device for a spherical hopping robot. Wiggin et al. [30] also used passive ratchets to design a 'smart clutch'. The smart clutch should store energy in the parallel springs to provide mechanical assistance during the stance phase, and allow free rotation during the swing phase.

C. Dog clutch

A dog clutch consists of two parts that match each others shape (see Fig. 2d). When the two parts are engaged, the relative rotation between the two parts is blocked; otherwise, the two parts can rotate independently. Dog clutches are discrete by nature, but have a large locking torque to weight ratio.

Although the dog clutch is a relatively unknown locking mechanism, it has been used in several robots. However, only examples of active dog clutches are found in literature. Elliott et al. [31] used such a clutch to attach and detach a parallel spring to the joint of a knee exoskeleton. Kossett et al. [32, 33] used a dog clutch to switch between two modes of the robot: ground mode and flight mode. A special type of dog clutch was designed by Kern et al. [34]. They use a rope that runs through several parts with mating surfaces. When the rope is pulled, the parts are pulled together, locking the parts. This locking device was inspired by the mammalian spine.

D. Cam-based lockers

Cam-based lockers consist of two separate cams that have complementary shapes and are engaged (see Fig. 2e, f and g). In principle, the engagement of the two cams can be actuated, resulting in an active cam-based locker. The examples found in literature, however, are passive cam-based lockers that lock due to the position of components of the lock. Although the working principle itself is independent of friction, the relative motion between the cams induces friction in the system. The shocks introduced at the transition between locked and unlocked phase are, on the other hand, relatively small compared to for example ratchets.

As described by Bickford and Martin [15, 16], a wide variety of intermittent mechanisms is equipped with a cam-based locker. Intermittent mechanisms consist of two members, the driver and driven member. As the name depicts, an intermittent mechanism transforms the continuous movement of the driver to an intermittent movement of the driven member. As such, the driven member has a dwell and a motion phase. During the dwell phase, a cam-based locker ensures the driven member is locked. A first example is the Geneva drive or Maltese cross, which is widely described in literature (see Fig. 2f). Another example of an intermittent mechanism with cam-based lockers is the mutilated gear mechanism (see Fig. 2g) which has

recently been adopted by Mathijssen et al. [35, 36] in a novel compliant actuator in order to lock parallel springs.

E. Hydraulic lock

A mechanical locking principle that is very different from the other principles is hydraulic locking. In hydraulic locking devices, the fluid is blocked by closing a valve in the hydraulic circuit. The advantages of hydraulic locks are that the locking force is high with respect to the actuation force and that the system can be locked in every position. However, such a lock can only be used in hydraulic systems, which are generally not very energy efficient.

Such a locking device was used by Mauch [37] in the SWING-N-STANCE above knee prosthesis. In this prosthesis, the knee is locked or unlocked, depending on the task that is performed. Another example of a prosthesis that uses an hydraulic lock is the Otto Bock 3R80 knee prosthesis [38], where a stance phase valve is closed when the body weight is put on the knee joint. When the body weight is removed, at the end of the stance phase, the damping is reduced and the knee is able to flex.

IV. Friction-based locking devices

Friction based locking devices depend on friction in order to prevent motion between two parts. As described in detail by Orthwein [17], the friction force can be generated using various mechanisms, such as disk brakes, drum brakes, cone brakes and band brakes. Since the amount of friction between two surfaces is limited by the normal force, friction based lockers generally have a limited locking torque. On the other hand, friction based lockers can lock at every position and can often be used as a controllable brake.

Most friction based locking devices have some kind of force amplifier, to amplify the actuation force perpendicular to the two surfaces, leading to a high friction. If no force amplification is used, the actuation force needs to be high. This section describes the friction based devices used in robotic applications, and indicates which are active lockers or passive lockers. The descriptions also include the type of force amplification that is used.

A. Electromagnetic brake

A well known type of brake in robotics is the electromagnetic brake. In this type of brake, two friction surfaces are engaged by the attractive force between a permanent magnet and an electromagnet. Such brakes are relatively simple and cheap, but often consume a relatively large amount of energy. An electromagnetic brake can be locked when powered, or locked when unpowered. Since at least switching from one state to the other requires activation of the electromagnet, an electromagnetic brake is considered active.

Multiple robots use an electromagnetic brake in parallel with a motor to either increase safety or decrease the energy consumption. Hirzinger et al. [39] used brakes on all joints of their robotic arm in order to increase the safety. These brakes make sure that the robot stands still when it is powered down. Sugahara et al. [40] used electromagnetic brakes on the joints of their bi-pedal walking robot to lower the energy consumption. When the robot stands still, the brakes hold the joints in place. Another reason for using electromagnetic brakes is to adjust the joint impedance. This was done by Morita and Sugano [41] on their robotic arm.

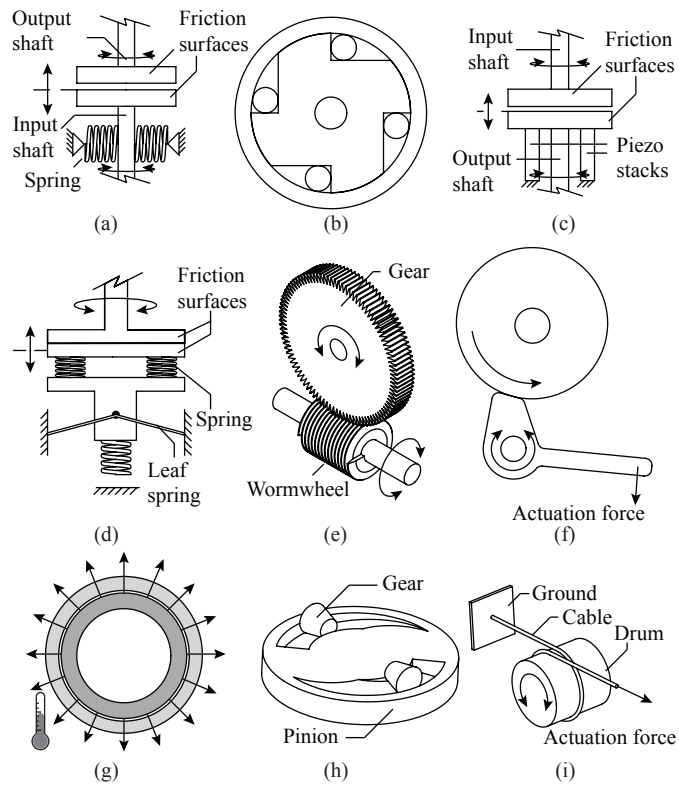

Fig. 3. This figure shows the types of friction based locking devices with: (a) a bi-stable brake, (b) an overrunning clutch, (c) a piezo actuated brake, (d) a thermic lock, (e) a wormwheel, (f) a self-engaging pinion-gear mechanism, (g) a self-engaging brake and (h) a capstan.

B. Overrunning clutch

An overrunning clutch has an inner and outer raceway similar to bearings, with cylinders or balls (rollers) between the two raceways and a wedge on one side (see Fig. 3b). The relative rotational speed of the two raceways determines whether the overrunning clutch is locked or not. The rollers of an overrunning clutch can also be pushed in the wedge using small springs or an actuator. The equivalent linear locking device uses a friction lever which is mounted around a translating stick. When this friction lever is rotated, it locks the stick.

An active overrunning clutch is the bi-directional overrunning clutch by Hild and Siedel et al. [42, 43]. In this clutch, the balls are replaced by wedges that can be placed in both directions, making locking possible in two directions.

In the asymmetric compliant antagonistic joint developed by Tsagarakis et al. [44], a two side acting passive overrunning clutch mechanism was deployed to achieve efficient regulation and maintenance of the pretension of the spring. As a result,

the electric motor is unloaded when not rotating, while still a low friction and highly backdrivable linear transmission system can be used for the motor. Controzzi et al. [45] designed a miniature passive overrunning clutch for the drives of robotic hand fingers. Li et al. [46], designed a knee brace for energy harvesting using an overrunning clutch. In the ankle prosthesis of Collins and Kuo [20] the linear variant of the passive overrunning clutch is used to store energy in a spring, lock the spring and release the energy at a specific moment during the gait. Another example is the knee orthosis by Shamei et al. [47], which uses a clutch to attach a support spring during the stance phase of the gait.

C. Non-backdrivable gearing

Non-backdrivable gearing are gears that can only be driven from one side. Deploying non-backdrivable mechanisms in robotic applications is often challenging due to the constraints on weight and dimension. Mostly lead-screw and worm drives (see Fig. 3e) have been employed. The non-backdrivability is due to the shear friction, which also results in a very low efficiency. As a result, non back-drivable gears are passive lockers.

There are two main reasons for using non-backdrivable gearing. Firstly, the non-backdrivability is a virtue to protect actuators during human robot interaction (HRI), such as in the social robot Probo [48] and the robot fingers designed by Morita and Sugano [49]. Secondly, the non-backdrivability avoids energy losses and overheating of the motors by static load cancellation. Examples are worm drives in the motors in the 1 DOF anthropomorphic arm by Gu et al. [50], the worm drive and lead screw after the variable stiffness motor in the MACCEPA actuator for the step rehabilitation robot ALTACRO [51], the powered elbow orthosis of Vanderniepen et al. [52] and reconfigurable robot of Baca et al. [53].

D. Self amplifying brakes

Some locking devices used in robotics are based on self amplifying brakes (see Figs. 3f and . 3h). While only a small force is required to engage both sides of the brake, the self amplifying effect enables to lock high forces. The self amplifying effect depends on the direction of the relative motion between the two components of the mechanism. In one direction, the mechanism will amplify the normal force since the friction between the two friction surfaces will pull them together. In the other direction, the mechanism will weaken the normal force and will therefore not lock as strongly. As such, this principle is suitable for one-direction locking only. An example of this is shown in Fig. 3f. When the small force to engage both surfaces is delivered by a spring, the amplifying brakes are passive. When this is delivered by a motor, the amplifying brakes are active and allow to not lock in either of both directions. The applications found in literature are active self ampifying brakes.

Kim and Choi [54] used an active self amplifying brake for a clutch in cars. In their clutch, the normal force is amplified by a wedge-like pinion gear mechanism, which transfers a relative rotational motion into a small translational motion, pushing the friction plates stronger together (see Fig. 3h). Peerdeman et al. [55] used an active self amplifying mechanism in their underactuated robotic hand to lock the joints of the fingers in order to perform certain grasps. This application is similar to the robotic hand discussed in section III-A.

E. Capstan

A special type of self amplifying brakes is the capstan. Capstans use the friction between a pulley and a cable to brake the cable with respect to the pulley (see Fig. 3i). When the cable is tightened around the pulley, the pulley pulls on the cable, which tightens the cable even more. In robotics, a capstan is mainly used as cable drive. Werkmeister et al. [56] and Baser et al. [57] studied the capstan drive stiffness and slip error respectively. A capstan cable drive is used, for example, in the WAM™ Arm from Barret Technology®, in an anthropomorphic dexterous hand [58], in a low-cost compliant 7-DOF robotic manipulator [59], and in a five degree-of freedom haptic arm exoskeleton [60].

By controlling the force on the cable, a capstan can also be used as an active locker. Instead of tightening the cable to increase the friction with respect to the pulley, the torsion spring is tensioned to reduce the outer diameter and wrap around the pulley. The elasticity of the spring facilitates the unlocking compared to a cable. However, locking requires more force due to the bending stiffness. This principle is used in the clutch on the parallel spring of the actuator proposed by Haeufle et al. [61].

F. Fluid brakes and clutches

Fluid brakes or clutches use a fluid which consists of micrometer-sized particles mixed with any kind of liquid. Of these fluids, electro-rheological (ER) and magneto-rheological (MR) fluids are studied most in literature. The fluid is placed around a rotating part like a shaft causing a small damping. By changing the electric or magnetic field around this fluid, the particles in it are aligned, which increases the damping. So by controlling the magnetic field, the damping of a joint can be controlled [62].

As predicted by Wang and Meng [63], fluid devices are currently being adopted increasingly in robotics applications. One of the applications is prosthetics where MR brakes are used to provide controllable resistance. This is for example interesting in a knee orthosis or prosthesis where significant portions of the gait consist of negative knee power, which can be delivered by a damper. This is done in the orthoses of Weinberg et al. [64], Chen and Liao [65], Kikuchi et al. [66] and the prosthesis of Herr and Wilkenfeld [67]. MR dampers are also incorporated in robotic arms [68] and haptic devices [69]. More recently a magnetic particle brake was installed by Shin et al. [70] in combination with Pneumatic Artificial Muscles (PAM) in a hybrid actuation concept to improve the control performance of the muscles.

G. Piezo actuated brake

Piezo actuated brakes use piezo actuators to create a normal force between two friction surfaces (see Fig. 3c). These actuators typically have a small stroke and therefore the alignment of the components is crucial. However, they are suited for generating a large force for a large amount of time, making them suitable for actuating brakes. The idea of a piezoelectric brake was already patented in 1989 by Yamatoh et al. [71] and was also used in the patented actuator of Hanley et al. [72]. Piezo actuated brakes are active lockers since an electric field should be provided to initiate the locking.

Piezoelectric brakes have been used in robotic applications as well. Firstly, such a brake was used in an early version of the DLR arm as a safety brake for when the power is down [73]. Secondly, the passive haptic robot PTER used piezoelectric brakes to brake its joints [74]. And finally, Laffranchi et al. [75] used a piezo actuated brake to vary the damping coefficients of joints. In order to do so, the normal force is varied, depending on the desired damping and the joint velocity.

H. Bi-stable brakes

One way to reduce the actuation needed for maintaining the normal force in friction based lockers is using a bi-stable mechanism (see Fig. 3a). Such a mechanism has two stable equilibrium positions with one unstable equilibrium position in between. It doesn't require force once the mechanism is switched, but requires force to switch from one side of the unstable equilibrium position to the other and is therefore an active locker. In bi-stable brakes, this spring is used to switch between the engaged and disengaged state of the brake.

This idea was already patented in 1973 by Parmerlee [76], but has not been widely used in robotics. Bi-stable locking devices have been used by Cho et al. [77] in electronics, to hold a lens in place in optical board-to-board communication. Although this example might not be very applicable to robotics, the principle can also be applied to larger brakes.

I. Statically balanced brakes

A friction based locking mechanism that completely decouples the friction force and the actuation force is the statically balanced brake by Plooij et al. [78] (see Fig. 3d). This brake comprises three groups of springs of which the total potential energy is constant. Therefore, all position of the brake are equilibrium positions, while the position of the brake determines the normal force between two friction surfaces. Since the actuator now only has to apply a force to move a small part, the energy consumption is very low. Although this brake has not been implemented in a robot yet, it is usefull in applications that require a low energy consumption, unlocking under load, a large amount of locking positions and an adjustable locking torque. The intended application of the brake is the locking of a spring in a novel parallel spring mechanism, which is currently being developed.

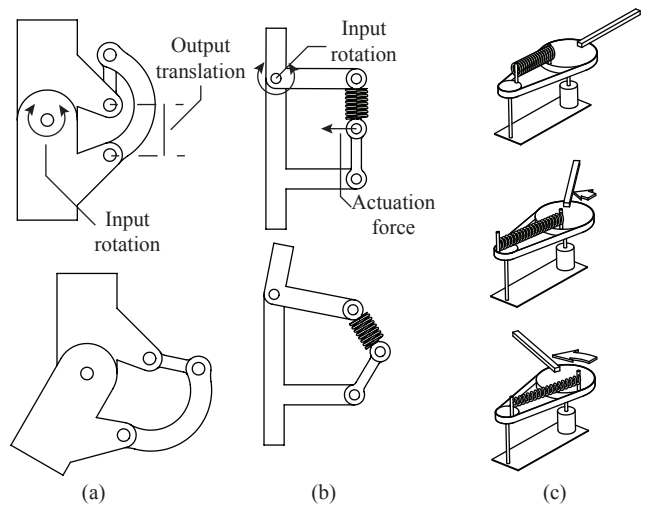

Fig. 4. This figure shows the types of singularity locking devices with: (a) and (b) two different four bar mechanisms and (c) a non-linear spring mechanism.

J. Thermic lock

The thermic lock uses the difference in thermal expansion coefficients of different materials to obtain a lock with force closure (see Fig. 3g). The mechanism consists of a shell that can freely rotate around a core. The material of the core has a higher thermal expansion coefficient than the shell. The temperature control is achieved by a resistance wire that heats up the brake and as such locking the joint. Since heating up and cooling down take time, the response time of these brakes is relatively large. There are no applications of this locking mechanism in robotics known to the authors.

V. Singularity locker

Singularity lockers are characterized by a position dependent transfer ratio. In its singular position such lockers have an infinitely high transfer ratio, featuring an infinitely high locking torque. This section describes the active and passive singularity locking devices found in literature.

A. Four bar linkage

One approach to realize singular positions is to use four bar mechanisms (see Figs. 4a and 4b). Such mechanisms typically have an input rotation and an output rotation or translation. In the singular position, three of the four joints of the four bar mechanism are aligned, resulting in an infinitely high transfer ratio from the input to the output. As soon as a singular position is reached, it is impossible to open the locking by applying torque on the input rotation. Only the action of an actuator pushing the linkages out of their singular position can open the system (e.g. a torque on one of the three aligned joints). Therefore, the four bar linkages are considered active lockers. Advantages of this mechanism are that the unlocking of the mechanism can be done when bearing its maximal load and with a very low energy consumption. Disadvantage is that

due to the nature of the system, the locking is only available in one angular position.

For these reasons this kind of locking device is used in robotics to lock the knee of a bipedal walking robot [79] and in the transfemoral prosthesis AMPFoot 2.0 for realizing the 'catapult' mechanism [80]. Instead of realizing in a short time a high power for the push-off phase, a smaller and less powerful motor loads energy in a locked spring during a longer lapse of time. In the successor AMPfoot 3.0 a passive version is used which is unlocked by hitting a mechanical stop when walking [81]. A second application is the weight acceptance spring in the knee of the Cyberlegs alpha prototype [82], of which the mechanism is shown in Fig. 4b. During the stance phase, the spring is attached to a linkage that can be held in place with only a small actuation force. During the swing phase, the four bar mechanism is unlocked so the linkage can rotate out of the way and the knee can quickly flex to provide sufficient ground clearance for the swing phase.

B. Non-linear transfer ratio

The use of singular postures of human arms is well-known to reduce the required joint effort and avoid muscle fatigue. This virtue in nature was used by Ajoudani et al. for a robotic manipulator in [83]. The kinematic degrees of redundancy are adapted according to task-suitable dynamic costs. Arisumi et al. used the singular postures of arms to avoid actuator saturation when lifting a load [84]. The non-linear transer ratio lockers are passive lockers.

Non-linear transfer ratios have also been used passively. A first example of this is the non-linear spring mechanism for robotic arms designed by Plooij and Wisse [85] (see Fig. 4c). This mechanism consists of two connected pulleys with a spring in between. The transfer ratio from the length of the spring to the rotation of the link becomes infinitely high at two positions and thus the spring is locked at those positions. They used this spring mechanism to reduce the energy consumption of the arm by adding a spring parallel to the motor. A second example is the variable stiffness actuator Compact-VSA of Tsagarakis et al. [86], where the stiffness regulation is achieved by a lever arm mechanism with a variable pivot axis. When the pivot moves, the non-linear amplification ratio of the lever changes from 0 to infinity. And thirdly, the knee of the humanoid Poppy by Lapeyre et al. [87] uses a spring in parallel to the knee, which locks the knee during the stance phase in a certain singular position.

VI. Comparison

In this section, the different types of locking mechanisms are compared on the criteria given in section II-A. Table VI lists all types of locking devices and shows how well they score on the criteria, with a score of $++$, $+$, 0, $-$ or $--$. A $+$ always indicates that the device scores well. For instance, if the energy consumption scores $++$, this means that the device uses (almost) no energy. The different locking principles (i.e. mechanical, friction, singularity) will now be discussed.

Mechanical locking devices typically have a low energy consumption. Even when they are actuated, the only thing the actuator has to do is position the blocking part, for instance the pawl. Furthermore, mechanical locking devices typically have low weight, are small, have a low price and their locking torque is only limited by the strength of the parts. However, such locking devices also have disadvantages. Firstly, they are hard to unlock while being under load because of the friction between the two interfering parts. Secondly, their number of locking positions is limited (exept for the hydraulic lock and the ratchet). And finally, the impacts that occur when a joint is blocked, will lead to shocks in the system.

Friction-based locking devices have less problems to unlock under load than mechanical lockers. This is due to the fact that the two friction surfaces can often be disengaged, releasing the lock. Another advantage of friction based lockers is that two friction surfaces can be engaged at any position and therefore the number of locking positions is infinite. And finally, since the locking torque depends on the friction coefficient and the normal force, the maximum locking torque can be controlled by controlling the normal force. As such, some friction based lockers can be used as controllable brakes. However, these advantages come with a downside. Firstly, since the friction surfaces have to be pushed together, the energy consumption of these locks is typically high. Secondly, the locking torque is limited by the available normal force between the friction surfaces. And finally, in general friction based lockers do not score well on size, weight and price.

Singularity lockers are less common in robotics, although they score well on unlocking under load and on the power consumption. Also, their locking torque is only limited by the strength of the parts, similar to the mechanical lockers. Disadvantages are that they typically have one locking position and that they are relatively large. So in comparison with the mechanical lockers, they can unlock under load, but are larger.

VII. Selection and development

This section provides guidelines for the selection of a locking mechanism and discusses current and future research directions.

A. Selection

Table VI lists all the advantages and disadvantages of the different locking mechanisms. As a guide for designers, Fig. 5 shows a flow chart that can be used for the selection of a suitable locking mechanism. Following the flow chart, designers will find the locking mechanism(s) that is most specifically suited for their application. However, there might be application specific reasons to prefer another mechanism. For instance, in an application with hydraulic actuators it would be logical to prefer a hydraulic lock instead of a latch, although the application might not require infinite locking positions. Let's now look at two examples from literature to see how this flow chart would have lead the designers to their choice.

TABLE I

THE COMPARISON BETWEEN THE DIFFERENT DEVICES MENTIONED IN THIS PAPER. IN ALL CASES, ++ MEANS THAT THE PROPERTY OF THE IDEAL LOCKING MECHANISM IS SATISFIED. FOR INSTANCE WITH RESPECT TO THE ENERGY CONSUMPTION, ++ MEANS THAT THE BREAK (ALMOST) DOES NOT CONSUME ENERGY.

Type	*Locking principle*	*Activation*	*# of directions*	*(Un)locking while under load*	*Cont. power consumption*	*Switching power consumption*	*# of locking positions*	*Size*	*Weight*	*Switching time*	*Price*	*Locking torque*	*Locking torque adjustable*
Latches	Mechanical	Active	1	−−	++	+	−−	+	+	++	+	++	−−
Ratchets	Mechanical	Active	1	−−	++	+	+	+	+	++	+	++	−−
Dog clutches	Mechanical	Active	2	−−	++	+	−	+	+	+	+	++	−−
Hydraulic locks	Mechanical	Active	2	−	++	+	++	+	+	0	+	++	−−
Latches	Mechanical	Passive	1	−−	++	++	−−	++	++	++	++	++	−−
Ratchets	Mechanical	Passive	1	−−	++	++	+	+	+	++	++	++	−−
Cam based	Mechanical	Passive	1	++	++	++	−	0	0	−	+	++	−−
Electromagnetic	Friction	Active	2	++	−−	+	++	0	−	+	0	0	++
Overrunning	Friction	Active	1	0	++	+	++	+	+	+	0	++	−−
Self amplifying	Friction	Active	1	+	++	+	++	0	0	+	0	++	−
Capstan	Friction	Active	1	+	++	+	++	0	0	+	0	++	−
Piezoelectric	Friction	Active	2	++	+	+	++	0	0	++	−−	0	++
Bi-stable	Friction	Active	2	++	++	−	++	0	0	0	−	0	−
Statically balanced	Friction	Active	2	++	++	++	++	0	0	0	−	0	++
Thermic	Friction	Active	2	+	−−	−−	++	+	+	−−	0	0	+
Overrunning	Friction	Passive	1	++	++	++	++	+	+	+	0	++	−−
Non-backdrivable gearing	Friction	Passive	2	0	++	++	++	++	++	+	+	++	−−
Four bar linkages	Singularity	Active	2	++	++	+	−−	0	0	−	+	++	−−
Non-linear transfer ratio	Singularity	Passive	2	++	++	++	−−	−	−	−	+	++	−−

Firstly, in the knee of the bi-pedal running robot Phides [22], a parallel spring has to be attached to the joint during the stands phase and detached during the swing phase. This does not require an adjustable locking torque; (un)locking does not have to be performed under load and the number of locking positions is one. Therefore, a latch was used.

Secondly, in the transfemoral prosthesis AMPFoot 2.0 [80], the joint has to be locked while a small motor loads a spring. This does not require an adjustable locking torque; since the spring is loaded, the ankle has to be unlocked while being under load and the number of locking positions is one. Therefore, a singular locking mechanism was used.

B. Development

There are four trends that can be observed from recent research and will likely dominate research in the (near) future. Firstly, the amount of robots that incorporate locking mechanisms is growing rapidly. This can be seen by looking at the publication dates of the citations. Secondly, new mechanisms were developed recently that require low actuation power, but have a larger applicability than conventional mechanical or singularity lockers. This is logical since locking mechanisms are frequently used in applications in which energy consumption is crucial. Thirdly, the use of singularities is a relatively new topic: the references date from the period 2008-2014. And fourtly, recently new actuator technology found its way into locking mechanisms. Examples include SMAs, piezo actuators and electro- and magneto-rheological fluids.

VIII. CONCLUSION

This paper presented an overview of locking devices that are used in robotics. The locking devices are divided into three categories: mechanical locking, friction-based locking and singularity locking. Each category that can be each be split into actuated lockers and passive lockers. The locking devices were then evaluated based on the properties of an ideal locking device. **Mechanical locking** devices use relatively few energy, are cheap, small and can lock high torques. **Friction based locking** devices can unlock under load, have an infinite amount of locking positions and can adjust the locking torque. **Singularity locking** devices can unlock while being under load, consume little energy and can lock high torques. A flow chart was provided that will help designers of robots to select a suitable locking mechanism and shows in which devices similar mechanisms have been used.

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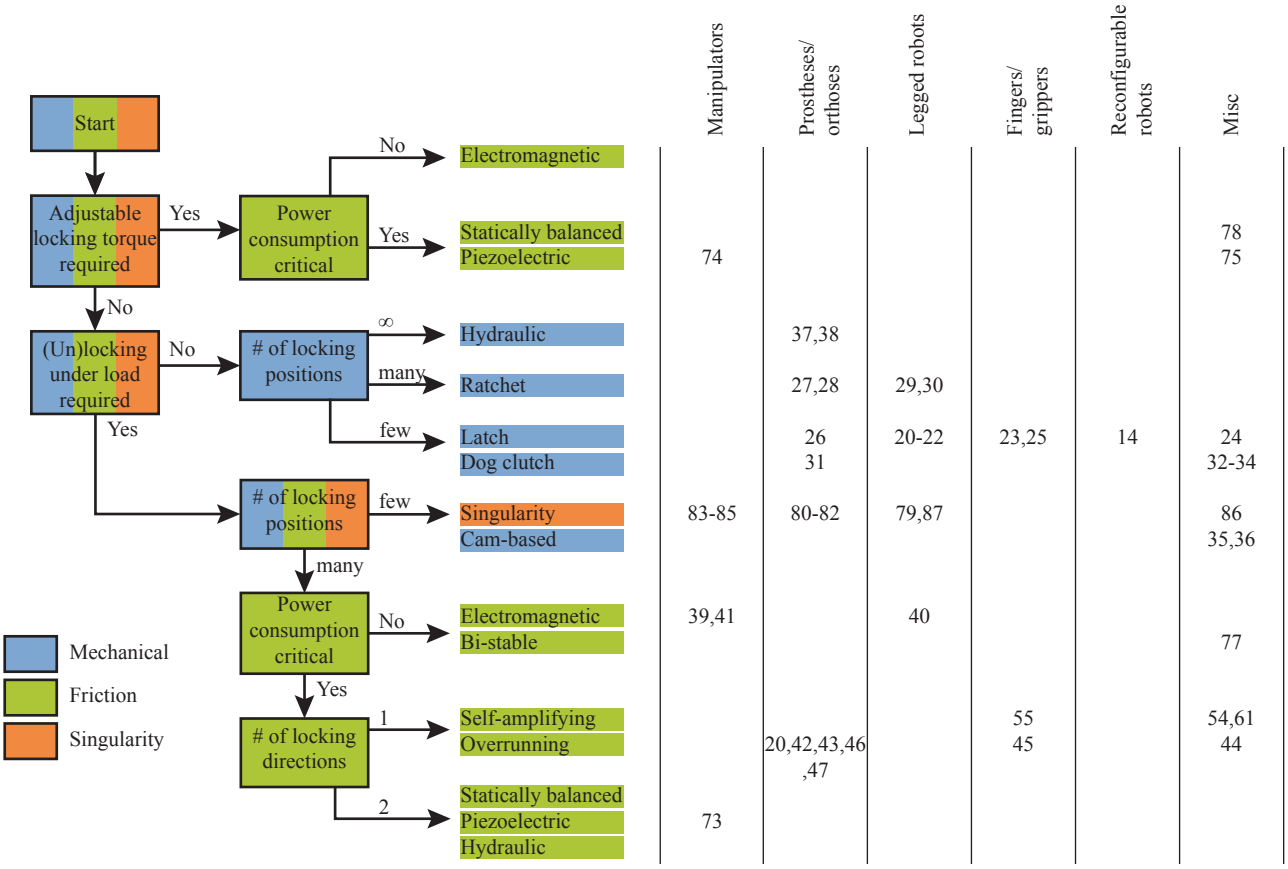

Fig. 5. Flow chart for selecting a locking mechanism. This chart will give the most specific locking mechanism. However, there might be application specific reasons to choose another mechanism. The references in which the mechanisms are currently used are listed on the right.

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