Series Clutch Actuators for Safe Physical Human-Robot Interaction

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Abstract—This paper presents the design, implementation and control of a device intended to mechanically improve the safety of serial robots interacting with humans. The device consists of an electronically adjustable torque limiter placed in series with each actuator, referred to as a Series Clutch Actuator (SCA). By appropriately adjusting the limit torques according to the robot’s configuration, the maximum static force that the robot can apply to its environment at the Tool Centre Point (TCP) can be limited to a prescribed safe level. If a limit torque is exceeded, the SCA slips and an emergency stop is triggered while the inertia located upstream from the SCA in the kinematic chain is mechanically disconnected. A method is presented to determine the optimal limit torques that maximize the isotropically achievable force (which can be applied in all directions without triggering any SCA) while satisfying the safe force limit. An approach to optimize the pose of a redundant robot in order to maximize the isotropically achievable force while preserving a safe maximum force threshold is also proposed. The design and fabrication of a torque limiter using a large number of friction discs is presented. Finally, the mechanisms are implemented into a 4-DOF redundant serial arm and preliminary experimental results are presented.

I. INTRODUCTION

There is currently a large demand for increasing direct physical interactions between humans and robots with the objective of improving productivity in manufacturing plants. An important limiting factor to the integration of robots in environments shared with humans is the potential hazards caused by current commercially available robotic manipulators. Even if sensors and artificial intelligence can be implemented with the objective of avoiding collisions, it is preferable, from a reliability standpoint, to design intrinsically safe robots, i.e. robots that are physically unable to hurt people during unexpected collisions. Both types of systems can be used together in order to minimize the number of collisions while guaranteeing safety if an unavoidable impact occurs.

A popular approach to create intrinsically safe robots is to make them compliant [1], [2], [3]. Indeed, compliance reduces the peak force attained during a collision. By extending the duration of the contact, it also allows the controller to sense it and react to reduce potential damages, under certain constraints (i.e., reaction time). However, adding compliance limits the precision and stiffness of the robot. Thus, a compromise must be achieved between safety and performance. Also, as explained in [4], compliant joints can store potential energy that allows them to reach higher velocities than their actuators. It can be argued that storing and releasing energy without proper controllability can result in an unsafe behaviour. Recent works [2], [3] produced compliant joints for which the stiffness can be modulated with a second actuator in order to minimize the compromise between safety and performances.

A more recent approach [5], [6], [7], [8], [9] consists in using torque limiters to create stiff robots that become compliant after a contact force threshold is reached. Placing a clutch in series with each actuator of a serial manipulator can be referred to as Series Clutch Actuators (SCA) [10], by analogy to Series Elastic Actuators (SEA) which consists in placing elastic components in series with each actuator to build compliant robots [1]. The advantage of a SCA is that it limits the forces applied on the end-effector without a reduced control bandwidth, induced vibrations or static errors due to the compliance of the SEA. A disadvantage of SCA is that the robot acceleration must be limited in order to prevent the inertial forces from triggering the clutch. As it can be seen in Fig. 1, SCAs allow high stiffness and precision for low interaction forces (under normal conditions) and high compliance and safety when the interaction forces exceed a preset threshold, for example during a collision. This approach thus circumvents the need of a compromise between precision and safety. A video accompanying this article presents collisions between a robot and a rigidly fixed body to further illustrate that SCAs have the potential to lead to safe and precise robots. Furthermore, the ISO 10218-1 standard [11](2006) states, as a sufficient condition for allowing human-robot collaboration, that the static force that can be transmitted at the TCP be limited to 150 [N] or lower. Limiting the achievable static force is thus an effective — and recognized — approach to obtain intrinsically safe robots.

Fig. 1. Contact force as a function of displacement for various joint types.

The main challenge with SCAs is that the force threshold at the TCP is direction and configuration-dependent. Indeed,
as the manipulator is moving, the shape of the achievable force space changes according to the Jacobian matrix. A possible solution is to use clutches for which the thresholds are adjustable online by the controller. However, changing the limit torques only translates the achievable force space’s boundaries without affecting their orientations. To further improve the shape of the achievable force space, SCAs can be used on a redundant manipulator whose secondary task is the improvement of the ratio between the minimum and maximum force thresholds [12].

In this paper, Series Clutch Actuators (SCAs) are implemented on a 4-DOF serial manipulator. The algorithms for adjusting the limit torques according to the robot’s pose are derived. A method to compute the articular displacements to optimize the manipulator’s pose for a certain Cartesian position is obtained. The design and fabrication of four compact clutches using a large number of friction discs is presented. Finally, the clutches are implemented on a 4-DOF serial robot and preliminary experimental results obtained from collisions on a rigid obstacle are presented.

II. COMPUTATION OF THE LIMIT TORQUES FOR A GIVEN CONFIGURATION

In this section, a procedure to compute the limit torques of the SCAs for a given configuration is presented. The — orientation-dependent — force threshold is bounded by \([F_{\text{min}}, F_{\text{max}}]\). The objective of the procedure is to compute the limit torques to set \(F_{\text{max}}\) to a pre-determined safe value while maximizing \(F_{\text{min}}\). The isotropic force threshold \(F_{\text{min}}\) is used as an optimization criterion because a collaborative robot is often required to apply forces in unpredictable directions.

For a manipulator using SCAs, the force \(f\) that can be applied at the TCP without exceeding any of the —assumed symmetric— limit torques is bounded by the following inequality:

\[
-\tau_{\text{max}} - \tau_g \preceq J^T f \preceq \tau_{\text{max}} - \tau_g,
\]

in which \(\tau_{\text{max}}\) is the limit torque vector, \(\tau_g\) is the gravity induced torque vector, \(J\) is the translational Jacobian matrix of the manipulator and \(\preceq\) is the component-wise less or equal relational operator. It can be shown that the limit torque for the \(i\)th joint, \(\tau_{\text{max},i}\), can be adjusted to satisfy an isotropically achievable force level \(F_{\text{min}}\) according to:

\[
\tau_{\text{max},i} = ||j_i||F_{\text{min}} + ||\tau_g,i||
\]

in which \(||j_i||\) is the 2-norm of the \(i\)th column of \(J\). The maximum force threshold \(F_{\text{max}}\) which characterizes the safety level, is reached when a force is applied at the TCP in a direction for which limit torques are exceeded simultaneously. In this situation, 3 inequalities of (1) become equalities:

\[
S_{ijk} J^T f = T_i S_{ijk} \tau_{\text{max}} - S_{ijk} \tau_g.
\]

In the latter equation, \(S_{ijk}\) is a \(3 \times m\) selection matrix whose \((1, i), (2, j)\) and \((3, k)\) entries are equal to 1 while all other entries are equal to 0. Matrix \(T_i\) is a \(3 \times 3\) signature matrix, \(i.e.,\) a diagonal matrix whose diagonal components are equal to \(\pm 1\). There is 8 possible combinations and \(T_i\) denotes a matrix whose diagonal components satisfy the following equation:

\[
\sum_{i=1}^{3} (T(i,i) + 1) 2^{(i-2)} = l.
\]

Solving (3) for \(f\) leads to:

\[
f_{ijkl} = (S_{ijkl} J^T)^{-1} (T_i S_{ijk} \tau_{\text{max}} - S_{ijkl} \tau_g).
\]

The largest force threshold \(F_{\text{max}}\) is thus defined as the largest norm of \(f_{ijkl}\) for which (1) is satisfied. If the limit torques are set according to (2), it is possible to find a quadratic relationship between \(F_{\text{max}}\) and \(F_{\text{min}}\), namely:

\[
(v_1^T v_1) F_{\text{min}}^2 + (2v_1^T v_2) F_{\text{min}} + (v_2^T v_2 - F_{\text{max}}^2) = 0
\]

in which

\[
v_1 = (S_{ijkl} J^T)^{-1} (T_i S_{ijk} \tau_g - S_{ijkl} \tau_g)
\]

\[
v_2 = (S_{ijkl} J^T)^{-1} (T_i S_{ijk} \tau_g - S_{ijkl} \tau_g).
\]

The values of \(i, j, k\) and \(l\) are not known \textit{a priori}. Therefore, it is required to explore each possible combination using the following algorithm:

1. For each possible combination of \(i, j, k\) and \(l\), compute \(F_{\text{min},ijkl}\) for the desired \(F_{\text{max}}\) by solving (6);
2. Compute each limit torque for the calculated value of \(F_{\text{min},ijkl}\) by using (2);
3. From the computed limit torques, calculate the corresponding \(F_{\text{max},ijkl}\):
   a. For each possible combination of \(i, j, k\) and \(l\), compute \(f_{ijkl}\) using (5).
   b. Verify if \(f_{ijkl}\) satisfies the constraint (1).
   c. \(F_{\text{max},ijkl}\) corresponds to the largest norm of \(f_{ijkl}\) which satisfies the constraint.
4. Choose the limit torques which give the largest \(F_{\text{min},ijkl}\) while satisfying \(F_{\text{max},ijkl} = F_{\text{max}}\).

III. OPTIMIZATION OF THE CONFIGURATION TO MAXIMIZE THE ISOTROPIC ACHIEVABLE FORCE

The procedure presented in the preceding section is useful to compute the limit torques for a given configuration. However, the maximum value of the isotropically achievable force \(F_{\text{min}}\) is configuration-dependent. Therefore, the ability of a manipulator using SCAs to apply forces to its environment depends on its pose, as it is illustrated in Fig. 2 for a 4-DOF spatial robot. On the figure and for two different poses, the achievable force spaces are represented as polyhedra. The inner spheres have a radius equal to \(F_{\text{min}}\), whereas the outer spheres (with only one half shown to improve visibility) have a radius equal to \(F_{\text{max}}\). From a geometric perspective, it is
desired to maximize the size of the inner sphere for a given outer sphere.

For a redundant manipulator, it is possible to use the additional degrees of freedom to optimize a performance criterion while following a Cartesian trajectory. In a recent paper [12], it was shown that it is possible to maximize the ratio $F_{\text{min}}/F_{\text{max}}$ while optimizing another index defined as:

$$\lambda = \det(\mathbf{U} \mathbf{U}^T)$$

in which $\mathbf{U}$ is the translational Jacobian matrix for which the columns were normalized to form unit vectors. The matrix is thus defined as:

$$\mathbf{U} = [ \mathbf{u}_1 \cdots \mathbf{u}_m ] = \left[ \frac{j_1}{\sqrt{j_1^T j_1}} \cdots \frac{j_m}{\sqrt{j_m^T j_m}} \right]$$

(10)

Knowing the manipulator’s kinematics, it is possible to optimize its trajectory by commanding articular displacements equal to the gradient of $\lambda$ projected into the null space of $\mathbf{J}$. By adding these displacements to those required to follow a Cartesian trajectory — obtained by the least squares solution —, we obtain the following articular displacements:

$$\delta \mathbf{\theta} = \mathbf{J}^T \delta \mathbf{p} - c(\mathbf{I} - \mathbf{J}^T \mathbf{J}) \nabla \lambda$$

(11)

in which $c$ is a factor adjusted to balance the weight of the two terms and $\mathbf{J}^T$ is the Moore-Penrose generalized inverse of $\mathbf{J}$. To simplify its computation, $\lambda$ can be written as the sum of all the $\lambda_{ijk}$ —the index $\lambda$ if only the columns $i, j$ and $k$ are considered— obtained from each combination of 3 of the $n$ columns of $\mathbf{U}$, namely:

$$\lambda = \det(\mathbf{U} \mathbf{U}^T)$$

(12)

$$= \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} \lambda_{ijk}$$

(13)

$$= \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} |\mathbf{U}_{ijk}|^2$$

(14)

$$= \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} \left( \mathbf{u}_i \cdot \mathbf{u}_j \cdot \mathbf{u}_k \right)^2$$

(15)

$$= \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} \left( \frac{j_i}{\sqrt{j_i^T j_i}} \cdot \frac{j_j}{\sqrt{j_j^T j_j}} \cdot \frac{j_k}{\sqrt{j_k^T j_k}} \right)^2$$

(16)

To obtain the gradient of $\lambda_{ijk}$, we take its partial derivative with respect to each articular variable $\theta_i$,

$$\frac{\partial \lambda_{ijk}}{\partial \theta_i} = 2 |\mathbf{U}_{ijk}| \frac{\partial |\mathbf{U}_{ijk}|}{\partial \theta_i}.$$  (17)

If $\mathbf{U}_{ijk}$ is invertible, we have [13]:

$$\frac{\partial |\mathbf{U}_{ijk}|}{\partial \theta_i} = |\mathbf{U}_{ijk}| \text{Tr} \left( \mathbf{U}_{ijk}^{-1} \frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i} \right).$$  (18)

From this expression, we need to obtain the derivative of $\mathbf{U}_{ijk}$ with respect to $\theta_i$:

$$\frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i} = \left[ \frac{\partial \mathbf{u}_i}{\partial \theta_i} \frac{\partial \mathbf{u}_j}{\partial \theta_i} \frac{\partial \mathbf{u}_k}{\partial \theta_i} \right]$$

(19)

$$\frac{\partial \mathbf{u}_i}{\partial \theta_l} = \frac{\partial}{\partial \theta_l} \left( \frac{j_i}{\sqrt{j_i^T j_i}} \right) = 2 \frac{\partial j_i}{\partial \theta_l} \frac{j_i}{\sqrt{j_i^T j_i}}$$

(20)

$$\frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i} = \left( \frac{\partial j_i}{\partial \theta_i} \right)^2 \frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i} - \frac{1}{2} \left( \frac{\partial j_i}{\partial \theta_i} \right)^2 \frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i}$$

(21)

It is thus only required to have an analytical expression for $\frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i}$ for each $i$ and $l$. For control purposes, we can successfully compute $\frac{\partial \mathbf{U}_{ijk}}{\partial \theta_i}$, $\frac{\partial \mathbf{U}_{ijk}}{\partial \theta_j}$, $\frac{\partial \lambda_{ijk}}{\partial \theta_i}$, $\frac{\partial \lambda_{ijk}}{\partial \theta_j}$, and $\nabla \lambda$. Finally, the articular displacements are obtained with (11).

IV. DESIGN OF THE TORQUE LIMITERS

Many clutch technologies are commercially available. However, most of them have a low torque-to-weight ratio, which makes them inappropriate for the current application. Indeed, adding large inertia components to the manipulator is counterproductive to the objective of designing intrinsically safe robots. Three technologies are present in the literature for large torque-to-weight clutches: compact magnetorheological clutches [14], multi-disc friction clutches [15] or safe joint mechanisms [7]. In the context of this project, it was chosen to use multi-disc friction clutches for simplicity. Since the objective of this work is to study the use of adjustable SCAs on a redundant manipulator, it was decided to build clutches without focusing on weight optimization in order to save time.

The design of the clutch is based on the concept proposed in [15]: a stack of discs alternatively connected to the rotor and stator and compressed by a small linear actuator. The two types of discs are illustrated in Fig. 3. They are designed with radii which overlap to create a small ring-shaped friction zone. The torque is transmitted from the friction zone to steel rods through a locating hole and slot. Since the rotor and stator each comprise 6 steel rods, 4 clearance holes are also included on each disc. It should be noted that only two rods are fit to prevent the force distribution on the discs from being overconstrained. The stack of discs is illustrated in Fig. 4. To detect the slippage of the torque limiter, a photo-interruptor is placed on the stator to detect the motion of a pin fixed on the rotor.

The maximum torque that can be transmitted through a multi-disc friction clutch is given as [16]:

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The static friction coefficient of aluminium is in the range of $\mu = [0.8, 1.2]$ depending on the normal pressure \cite{17}. For this application, the lower bound was used, considering the low pressure applied on the friction zone. The discs are designed with $r_o = 0.0324[m]$ and $R_i = 0.0292[m]$. The number of discs in the stack was set to $N = 46$. The maximum force provided by the small linear actuator is $f_{discs,max} = 24[N]$. Therefore, the maximum limit torque as computed using (22) is $22.7[Nm]$. Fig. 5 presents one of the clutch prototypes in the fully-released and fully-compressed states.

Each clutch was calibrated by applying a force measured with a dynanometer at the tip of a lever. The reference voltage of the linear actuator’s potentiometer was varied and the limit torque was measured for a decreasing and increasing voltage to quantify the hysteresis effect. Before each measurement, the actuator position was changed successively from the uncompressed to the compressed states and vice-versa. This procedure was found to reduce the hysteresis effect and therefore it was also implemented in the 4-DOF robot controller as it is explained in the next section. For each clutch, a reference curve was computed by performing linear interpolations between the increasing and decreasing voltage data points and by calculating the mean of these two values for each voltage. The experimental data and computed reference curve are pictured in Fig. 6 whereas the reference curves for all clutches are shown in Fig. 7. On the latter figure, a dashed line is plotted at the minimum measured limit torque and another dashed line represents the theoretical curve at an arbitrary abscissa location. The reason for which the experimental curves are not linear is that the discs are not perfectly flat. The discs stack thus behaves as a non-linear spring in series with the springs which are mated on the part pushed by the actuator.

Even if the hysteresis effect was found to be significantly large — the limit torque is adjusted with a precision of $\pm 10\%$ —, the current design is appropriate for the application described in this paper. Indeed, a safety margin can be included in the limit torques to certify that the maximum static force will never be exceeded. However, the hysteresis effect can significantly reduce the performances of the manipulator as quantified by the value of $F_{min}$. Therefore, the design of the torque limiter should be modified to improve the precision of the limit torque. Possible modifications to
the current design include: using ball bearings instead of plain bearings, applying a heat treatment on the steel rods to reduce axial friction and improving the discs’ flatness. However, it is difficult to predict the maximum level of precision of a friction-based torque limiter. Current research in other torque-limiting technologies [7], [14] could lead to more accurate SCAs. Also, the weight of the torque limiter prototype is 0.9 kg. Because adding weight to the manipulator is counterproductive to the objective of building safer robots, the design should be optimized in order to minimize the additional mass. However, in the scope of the project described in this paper, the torque limiters introduced above are deemed precise enough and sufficiently lightweight to study the optimal use of SCAs on a serial manipulator.

V. IMPLEMENTATION ON A 4-DOF SERIAL MANIPULATOR

The four torque limiters described in the previous section were installed in series with the actuators of an existing 4-DOF serial manipulator. The D-H parameters of the manipulator are given in Table I while the architecture and a picture of the robot are depicted in Fig. 8. Because the articular torques caused by gravity can significantly reduce the effectiveness of SCAs — or any other safety system based on force limitation —, a counterweight was added to partially compensate the effect of the manipulator’s weight on the second joint.

The pressure on the disc stack is determined by the small linear actuator’s position, which is controlled using a bang-bang scheme. The reference potentiometer voltage is linearly interpolated from the experimental curve for a given limit torque, which is computed using the procedure described in section II. The limit torques are computed on a slave computer, which communicates in real-time with the master system. The robot itself is controlled using a position scheme to perform simple articular trajectories. As the configuration changes, the limit torques are adjusted to optimize the shape of the achievable force space. If a slippage (due to an excessive external force) is detected on any torque limiter, the current sent to the motors is immediately set to zero by the controller. Because gravity is partially compensated, joint friction prevents the manipulator from collapsing. The operator is required to manually bring the triggered torque limiter back to its reference position (defined by the photo-interruptor location) in order to reactivate the robot. This type of passive reaction is preferred because the robot behaviour is easy to predict by a person interacting with it.

Preliminary experiments suggest that the safety system functions correctly. Collisions were performed against a rigid body fixed to the ground. The contact force was measured using a force/torque sensor placed between the end-effector and a small impactor. Fig. 9 shows the amplitude of the force as a function of time for a collision occurring at a small velocity. The time at which the collision is detected by the photo-interruptor is outlined on the graph. As expected, the contact force decreases and stays under the threshold as the current sent to the motors is set to zero by the safety system.

VI. FUTURE WORK

Even if preliminary results showed that the proposed safety system works as expected, further experiments are required to evaluate the effectiveness of the proposed approach. Collisions will be performed at different velocities...
and limit torques to determine if SCAs are effective for dynamic impacts. For a given configuration, forces will be applied in many directions to reproduce the achievable force space and thus verify the ability of SCAs to control its size and shape. Also, the torque limiters will be calibrated for different configurations to measure the effect of transversal moments (due to the weight of the links) on the limit torques.

The method proposed in section III to compute articular trajectories to follow a Cartesian path while optimizing the isotropically achievable force $F_{\text{min}}$ will be implemented in the controller. The computation time of this procedure will be measured to verify if it can be used in real-time.

VII. CONCLUSION

In this paper, the concept of using Series Clutch Actuators (SCAs) — i.e electronically adjustable torque limiters in series with each actuator of a serial manipulator — was proposed. By appropriately adjusting the limit torques for a given configuration, it is possible to limit the maximum static force that can be applied at the tool centre point. The advantages of using SCAs instead of Series Elastic Actuators (SEA) are: a preserved control bandwidth, no vibrations and no additional static error. Also, when a high velocity collision occurs, the inertia located upstream from the triggered torque limiter in the kinematic chain is mechanically disconnected and does not affect the contact force amplitude.

A method to compute the limit torques for a given configuration to set the maximum static force threshold $F_{\text{max}}$ while maximizing the isotropically achievable force $F_{\text{min}}$ was presented. A procedure to optimize the pose of a redundant robot to maximize $F_{\text{min}}$ for a given Cartesian position was derived. The design, fabrication and calibration of four SCAs was performed. Finally, their implementation on a 4-DOF serial manipulator and preliminary experimental results were presented.

It is unclear if torque limiters based on friction between multiple discs constitute the most suitable technology for this application due to their lack of precision. Even if the design can be improved, it can be argued that the variability of a system based on friction can only be reduced to a certain extent. Other possibilities should be considered such as magnetorheological fluid clutches or other safe joint mechanisms.

Even if some limitations were pointed out, preliminary experiments suggest that the implementation presented in this paper is successful. Further tests will be performed to evaluate more precisely the effectiveness of the proposed approach.

REFERENCES