Effects of various factors on Power and Force Limitation function of collaborative robots

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ABSTRACT

The implementation of a collaborative robot application and the resulting man-robot proximity can give rise to a number of risks, including the risk of impact and crushing for operators or third parties moving around in the robot's environment. Various means of protection are available to integrators to limit the effects of possible contact between man and robot, including the power and force limitation function (PFL). Diversities of technologies used by manufacturers and their possible limitations, as well as the difficulties encountered by integrators in setting parameters led INRS to conduct a study identifying the factors that may affect the PFL function. To address this issue, a dedicated test bench was designed and experimental tests were conducted to measure the impact of each parameter.

1 INTRODUCTION

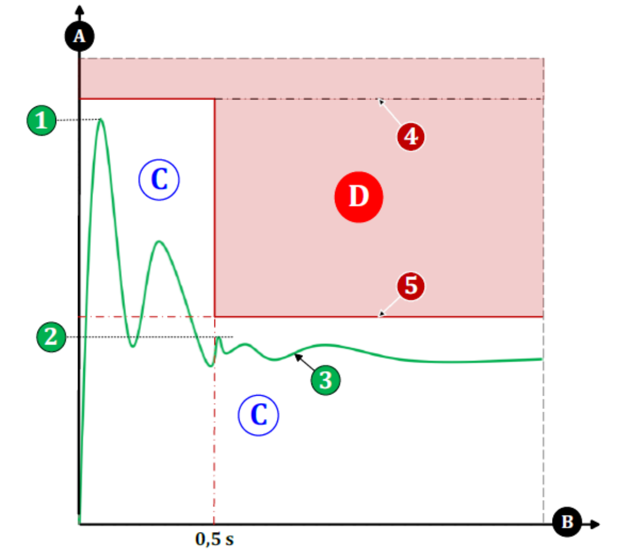
Depending on the results of the risk analysis, it is possible to human-robot contact as part of the implementation of a collaborative robotics application. These contacts can be classified into two categories:

- constrained contact: crushing of a part of the body between the robot and a fixed element in its environment.
- unconstrained contact: an impact between a moving part of the robot and a person.

The technical document ISO TS 15066 [1] divides all human-robot contact into two phases (see figure 1):

- a transient phase: the initial contact phase which occurs over a time period lasting up to 0.5 s,
- a quasi-static phase: the more stable phase of contact that follows the transient phase.

For each of these phases, the technical document ISO TS 15066 defines admissible force threshold values according to the parts of the body exposed. The admissible force threshold value for the transient phase is double that of the quasi-static phase.



A : Force or pressure
B : Time (s)
C : acceptable region for force or pressure
D : unacceptable region for force or pressure

1 : actual transient value (F_{TA} or P_{TA})
2 : actual maximum quasi-static value (F_{SA} or P_{SA})
3 : sample force or pressure
4 : transient limit (F_T or P_T) for relevant body region
5 : quasi-static limit (F_{max} or P_{max}) for the relevant body region

***Figure 1**. Graphical representation of force and pressure limits.*

If the force or the pressure is exceeded, the power and force limitation function (PFL) triggers a safety stop of the robot. The robot stop can be triggered immediately after contact detection or after a slight backward movement of the robot following contact detection, to allow the operator to disengage from the robot in the event of a crush.

This article presents the results of measurements conducted on two robots, using different PFL technologies, in both constrained and unconstrained contact situations. The main objectives of this experimentation are to:

- ensure that the measured force values do not exceed the threshold values programmed into the robot (based on the theoretical values as defined in the technical specification ISO TS 15066),
- identify the factors, including the robot's configuration parameters and trajectories, that may have a potential significant impact on the actual force values and on the behaviour of the PFL safety function.

It is important to highlight that the present study focuses essentially on contact forces. As pressure measurements are not easily interpretable, it was decided not to include this element in the current study.

2 PROTOCOL DESCRIPTION

2.1 Test configuration

In order to carry out the planned experiments, a test bench was built. It is made up of a plate that can be used to fix the robot base and the measuring device in different test configurations. The robot is equipped with a tool designed to mount a set of cylindrical tips with precisely defined circular contact surfaces. These tips are easily interchangeable and offer a range of contact surfaces: 0.5 cm², 1 cm² or 2 cm².

The pressure and force measurement device (PFMD) used for this experiment complies with the requirements mentioned on the annex N of the ISO/FDIS 10218-2 [2]. Depending on the nature of the contact to be assessed, the PFMD may be fixed for constraint contact or moveable for unconstrained contact.

When fixed, the PFMD is mounted to a rigid support structure that secures it from displacement and vibration. When moveable, the measuring unit supporting the PFMD is not affixed to a rigid supportive structure and, thus, can freely move in the direction of the force resulting from the collision. In order to match the total mass of the measuring unit to the effective mass of the part of the human body under test, a system for variable weight has been designed (see figure 2).

Figure 2. *Fixed PFMD and moveable PFMD.*

2.2 Preliminary tests

Before starting the force measurements, we carried out a series of preliminary tests to check the repeatability of the measurements. These tests showed that the maximum standard deviation over all the measurements is 7.71 N and that the standard deviation over the highest force values (the most relevant values for our study because they are potentially the most dangerous) is 0.59 N. These values are compatible with the recommendations mentioned in ISO PAS 5672 [3].

2.3 Factors to be tested

A number of factors have been identified as having a potential effect on the effective force applied by the robot in the event of a collision. These factors are of two types: firstly, the robot's trajectory profile, which may play a role in contact detection, and on the other, parameters that may have an effect on the PFL safety function.

In order to assess the effect of the robot's trajectory profile on the effective contact force, several configurations were defined:

- Vertical trajectories with different robot extensions,
- Vertical trajectories with contact at different heights (lower or upper the base),
- Horizontal trajectories with contact at different heights,

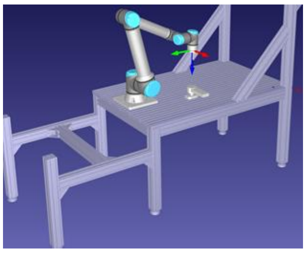
- Lateral trajectories with contact at different heights,

A number of parameters expected to have an effect on the actual collision force were identified as follows:

- $F_{threshold}$: programmed force threshold value (N),
- V: programmed tool center speed value (mm/s),
- P: programmed power threshold value (W),
- Q: programmed quantity of movement threshold value (kg.m/s),
- A: tool centre acceleration phase (acceleration, constant speed or deceleration),
- S: contact surface (cm²).

2.3 Test protocol

In order to achieve the two objectives set out above, we first defined a reference situation. The robot moves vertically at a constant speed. The robot's extension is intermediate, and the parameters have been set as follows:



- $F_{threshold}$: 110 N,
- V : 220 mm/s,
- P : 180 W,
- Q : 80 kg.m/s,
- A : 0 m/s² (constant speed),
- S : 0.5 cm^2

Figure 3*. Configuration for the reference situation*

Based on that reference situation, a series of measurements was carried out, varying each factor that could have an effect on effective contact force. For this purpose, the "one-factor-at-a-time" approach was adopted to simplify the measurement protocol [4].

All the tests performed in this experimental campaign were conducted on two collaborative robots (equipped with the PFL function) that are representative of the robots present in French industry. To be as representative as possible, the two chosen robots used different technologies for force detection (force sensors and motor current measurement).

3 MEASUREMENT RESULTS

3.1 Constrained contact

A first step was to realize collision tests in the reference situation defined above, i.e. in the vertical plane at a constant speed and with intermediate extension of the robot arm. In these tests, we only varied the force threshold value programmed into the robots between 100N and 250N, corresponding to the representative values for all the parts of the body (see ISO TS 15066).

The behaviours of the 2 robots were similar; the actual force value measured exceeds the programmed force threshold value, and the lower the programmed threshold value is, the greater will be the difference between these two values (see figure 4).

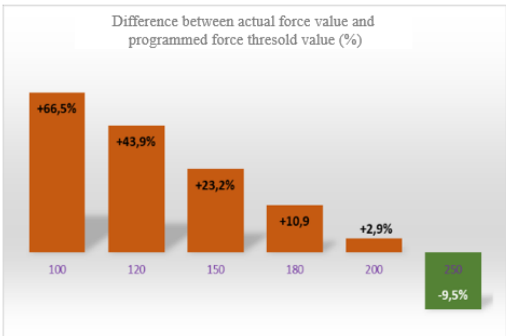


Figure 4*. Difference between actual force value and programmed force threshold value for different values of force threshold*

The second step consisted in performing constraint collision tests by varying the various factors that could have an effect on the effective contact force. The results of these collision tests led to the following observations:

- The tests revealed that the speed parameter has a significant impact on the actual force measured. We noticed, on one robot, for example that by varying the speed parameter from 160mm/s to 700 mm/s, we can see that the value of the real actual force measured varies from 250 to 490 N when the force threshold value is 100 N (see figure 5).

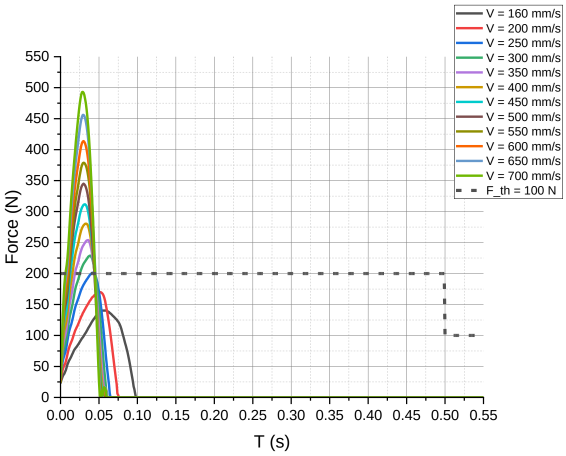
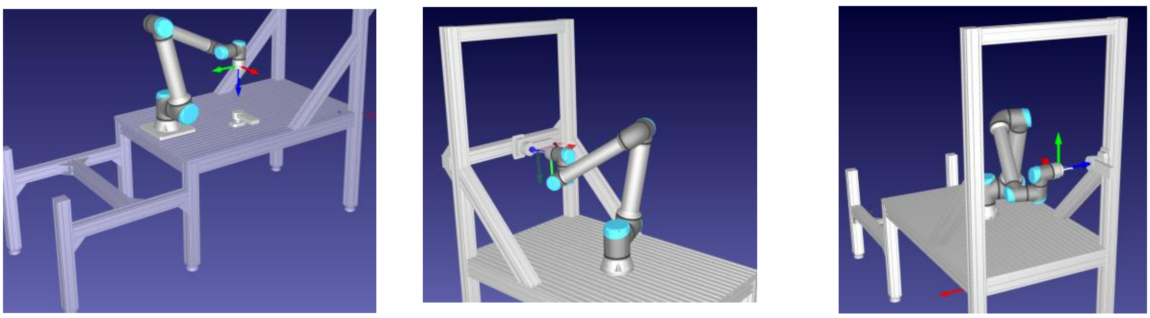


Figure 5*. Speed effect on the PFL function*

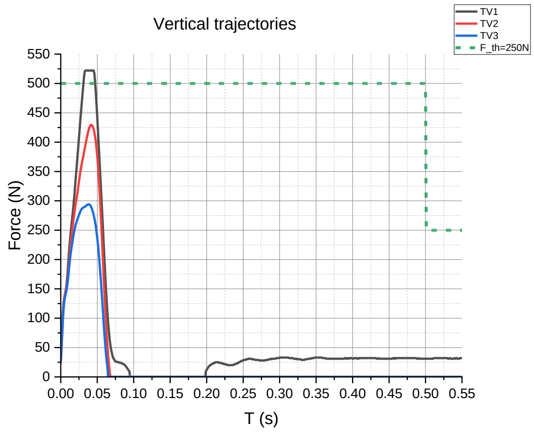
- The setting range for power parameter may vary depending on the robot model, from 50W to 1600W. In the reference situation used for the experiment, modifying this parameter does not change the behaviour of the PFL function; the actual force values measured do not vary according to the programmed power.
- The moment parameter has little impact on the actual force values measured. On the first robot model, no significant influence of the moment on the effective force was observed. Meanwhile on the second robot, a decrease in the force values measured was noted when the value of the moment parameter became very low (a few kg.m/s over a range varying from 0 to 100kg.m/s). This decrease can reach 30% of the maximum value of the real force measured.
- In the event of contact during the acceleration or deceleration phases, the actual force values measured are lower than in the case of constant speed. In both cases, this can be explained by the fact that the robot did not have time to reach the programmed maximum speed.
- The size of the surface contact has no impact on the actual force value measured.
- Several trajectory profiles were tested: vertical, horizontal and lateral trajectories (see figure 6). For each profile, measurements were taken at different robot extensions.



Vertical trajectory Horizontal trajectory Lateral trajectory

Figure 6*. Trajectory profiles*

Whatever the profile tested, it can be seen that the closer the point of impact is to the base of the robot, the higher the actual force measured. This can result in the programmed threshold value being exceeded when the extension is low (see figure 7).

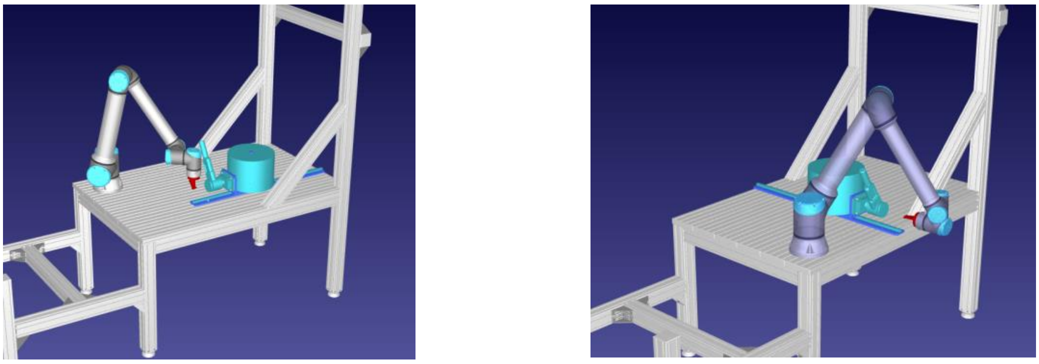


- TV1 : reduced extension
- TV2 : intermediate extension
- TV3 : major extension

Figure 7*. Impact of extension on the measured force values for a vertical trajectory*

3.2 Unconstrained contact

Unconstrained collision tests were carried out for masses ranging from 5kg to 75kg. Only horizontal and lateral trajectories on the reference platform were considered (see figure 8).



Horizontal trajectory Lateral Trajectory

Figure 8*. Trajectory profiles*

The findings are common to both robots. Regardless of the body part involved in the contact (and therefore the mass involved), the programmed speed have a significant influence on the measured force value; the higher the speed is, the greater the actual force measured is. The force threshold value programmed into the robot also has an influence, particularly when the mass is large and the programmed force threshold value is low.

Nevertheless, in most cases, the programmed force threshold values were respected by the PFL function i.e. the effective force values remain below the programmed force thresholds.

It is interesting to point out that the PFL function is not always triggered in the event of a collision. In some cases, the robot pushes the device without triggering a stop, especially when the experiment involves low-mass.

4 KEYPOINTS AND RECOMMANDATIONS

During our tests on constraint contacts, we observed that most of the measured force values exceeded the programmed force threshold values, despite compliance with the calculation method based on the model specified in ISO TS 15066 [1]. This was the case for both robots.

Speed, programmed force threshold value, acceleration and trajectory profile are parameters that influence the measured force value.

- programmed force threshold: the difference between the measured force value and the programmed force threshold value is greater the lower the programmed force threshold value. In other words, the lower the programmed force threshold value (more sensitive part of the body), the more difficult it will be for the robot to comply with this value;
- speed: the higher the robot speed, the higher the measured force value. It can be seen that at high speeds the robot is no longer able to comply with the ISO TS 15066 threshold values (see figure 5).
- acceleration: the measured force value is at its maximum when the robot's acceleration is zero. In other words, when the robot has reached its set speed. The measured force value is much lower during acceleration and deceleration;
- trajectory profile: the trajectory influences the measured force value. The most critical situations arise when collisions occur close to and below the level of the robot base.

Conversely, we found that the parameters "power", "moment" and "contact surface" had very little influence on the actual force value measured.

On the other hand, the programmed force threshold values were generally respected for unconstrained contacts.

The calculation method proposed in ISO TS 15066 provides an initial approximation of the speed to be programmed on the robot in order to comply with the thresholds. But, given the differences observed between the programmed force threshold values and the actual measured values, it is imperative for the integrator of collaborative robot application to perform validation measurements before the installation is commissioned. These measurements must be realized on the final application, in real conditions. As mentioned above, we have found that trajectories and acceleration phases (positive, negative and zero acceleration) can influence the measured value, that’s why tests carried out in non-representative conditions could lead to unrepresentative measurement results.

It should be noted that the force measurements of unconstrained contacts show that the force values measured comply with the programmed threshold values. However, these results need to be placed in the context. The tests were carried out using a sensor with an initial speed of zero, i.e. the operator is assumed to be stationary when the collision with the robot occurs. In real-life conditions, the operator could be moving toward the robot before the collision. It would therefore be necessary to reduce the robot's speed by a value corresponding to the potential speed of movement of the operator, given that ISO TS 15066 [1] specifies that the speed calculated using the mechanical model is a relative speed.

It is also important to remind integrators that the PFL is not the only existing preventive measure for reducing the effects of a collision. It could be complemented by intrinsic preventive measures such as, for example, increasing contact surfaces, reducing contact energy by using absorbent materials or reducing moving masses, all of which are measures to be favoured.

6 REFERENCES

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