Design of Safe Reactional Controller for Chamber Pressure in Climbing Robot CREA

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Keywords: CREA, Climbing Robots, Nonlinear Control, Chamber Pressure Control, Sealing, Reservoir Pressure, Suction System.

Abstract: CREA robot is designed to climb up concrete walls. The robot uses the suction mechanism to provide adhesion and wheel mechanism for locomotion. Eleven chambers which are connected to one common reservoir are responsible to produce adhesion force. A controller is developed to independently control each chamber while satisfying certain criteria on the safety of the robot. It is also designed to reach minimum friction between active inflatable seals and wall. In conclusion, the controller is able to successfully meet the conditions of stability, minimum friction and safety.

1 INTRODUCTION

Climbing robots are one of the robotic fields that despite the long period of research and practical attempts, engineering and industrial solutions are still scarce. This paper is reporting an early research on a promising climbing robot CREA. The robot is constructed by the cooperation of three major industrial partners and our robotics lab in University of Kaiserslautern. It is developed for inspection of large-concrete walls on dams, motor-way bridges, cooling towers and etc. The development of this robot is based on incremental research over almost 10 years and it is an adventurous attempt to improve the performance of its successful predecessor CROMSCI.

The Climbing robots, depending on their application, use various locomotion and adhesive mechanisms. For climbing a wall with even surface wheel-driven locomotion is predominant due to its high speed and manoeuvrability. This kind of locomotion requires especial adhesion system that produces adhesive force without effecting the continuous motion of the robot. As an adhesive system, suction methods are widely used for climbing robots with high payloads and heavy bodies. Nevertheless it is highly energy consuming and generates undesirable noise. Other methods like vortex and electro-adhesion have not yet been maturely developed for real practical applications. A complete survey on climbing robots is available in (Schmidt and Berns, 2013). CREA uses wheel-driven locomotion and highly sophisticated suction system with eleven chambers with active inflatable seals.

Passive suction systems generate adhesive force by sucking the air in to the suction cup and reducing the inside pressure. We call this mechanism perfect sealing since the suction cup is completely sealed and airflow path with ambient air is completely closed.

In order to be able to move, the perfect sealing should be avoided. This means that while the seal itself limits the airflow gap it should not completely close the flow path. By decreasing the leakage area the flow speed rises and therefore due to Bernoulli principle the pressure inside the chamber falls down. This principle is the basis for adhesion system of robots like Alicia^3 (Longo and Muscato, 2006), city climber (Morris and Xiao, 2008), CROMSCI (Schmidt, 2013) and also CREA. The challenges in this form of suction system is first to develop a seal that can control the chamber's air leakage and second to produce the large amount of airflow. Seals are normally in contact with the ground and it is desirable to have the least possible contact to reduce inhibitory seal friction. Both city climber and Alicia^3 use bristle seals to reduce the friction but at the expense of high airflow. However, when the size of the robot increases, generating such a big airflow is not beneficial. CROMSCI with a weight of 60 kg has a one seal for all seven chambers, it is designed to significantly reduce the air leakage area to gain under-pressure with much less power but at the cost of increasing friction. In conclusion reaching a desirable under-pressure or a reasonable sealing is in contrast with seal friction and has to be carefully studied.

CREA uses active seals for each eleven chambers to have a better control over the air gap between wall and the chamber to make better trade-off between friction and under-pressure. In (Kopietz, Schmidt, Schütz and Berns, 2014) an early work has been published on how to control these two contradictory phenomena in CREA. Here we will comprehensively analyse the suction system of CREA and develop a stable nonlinear controller to generate adhesive force with minimum possible seal friction. This novel method is straight forward with stability proof and also has simple architecture with less number of parameters than the method proposed by the previous work.

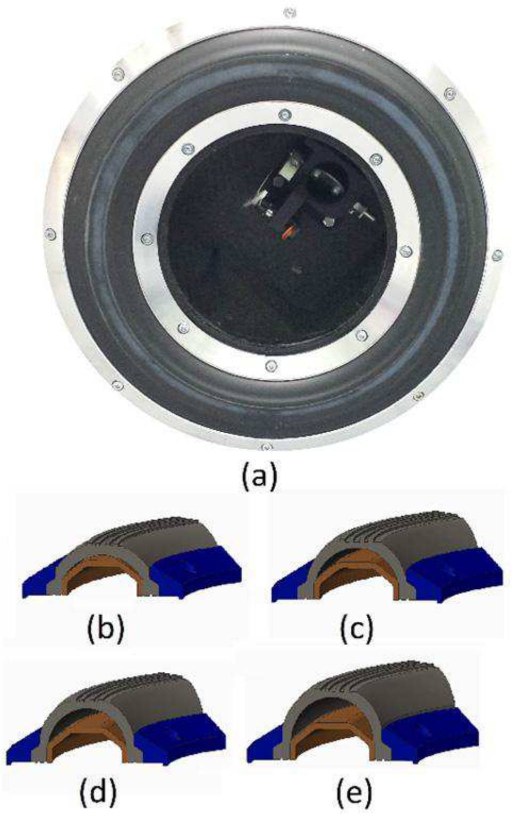

Figure 1: (a) The suction chamber of CREA which consists of black seal and chamber valve placed inside the chamber. (b) - (d) shows the CAD model of seal and how it inflates.

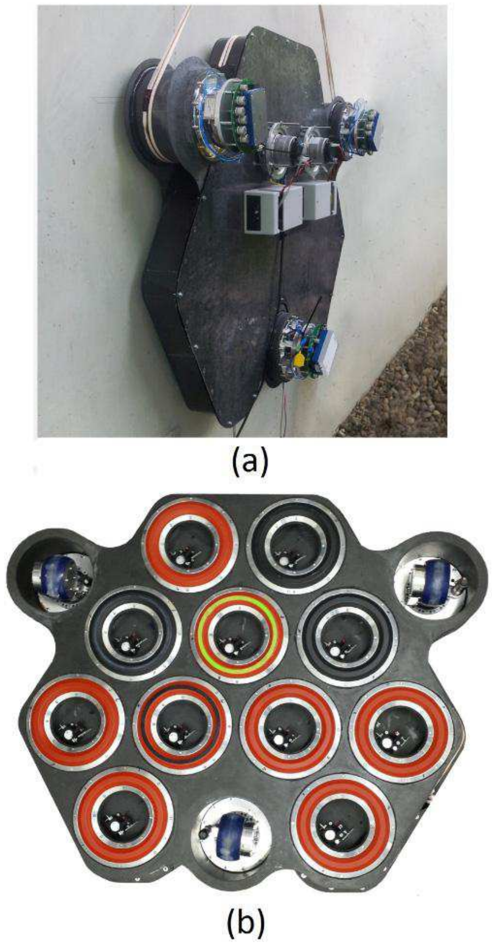

Figure 2: a) CREA robot on the wall. b) Bottom view of the robot where chambers have different types of seals.

2 SUCTION SYSTEM OF CREA

CREA has eleven chambers which generate under-pressure to exert adhesive normal force. Each chamber is connected by control valve to the reservoir. This valve controls the airflow area between reservoir and chamber. Typical value of pressure in the reservoir is -150 mbar and in the chambers is -10 to -100 mbar with respect to ambient air pressure. Throughout the paper the absolute value of the chamber or reservoir pressure is called *under-pressure* since it is always below the ambient air pressure. Three suction pumps are responsible for generating airflow and keeping the reservoir pressure around its nominal value. The most important part of the suction system are the seals. High pressure air (3bar) is used to inflate the seals controlled by switching valves (figure 2). Seals are responsible to adjust the air leakage between chambers and ambient atmosphere. Depending on the surface and the chamber pressure these seals have contact with the wall and hence introduce inhibitory friction which reduces the mobility of the robot. If the seals continue to inflate after their contact with wall, they start to push the robot away from wall which can cause the wheels to lose their contact and consequently the robot will be unable to move.

In CROMSCI one all-embracing seal is used for the seven chambers. If a chamber moves over a hole or a step (obstacle) it will lose under-pressure but CROMSCI is unable to adjust the seal inflation since other chambers are also coupled to this seal and any change in inflation can cause all others to lose pressure too. In CREA since each chamber has its own seal this problem never arises and the robot has more ability to adapt itself and move over various obstacles where chambers can independently adjust their under-pressure and seal inflation.

The electric energy of suction pumps together with high pressure supply for seal inflation is provided by a safety cord. In climbing mode, robot produces under-pressure in its chambers to provide enough negative normal force to attach the wheels to the wall. If the negative normal force is enough, the wheels will have enough friction to push the robot up. It is desirable to generate as big as possible adhesive force or accordingly high under-pressure in the chambers.

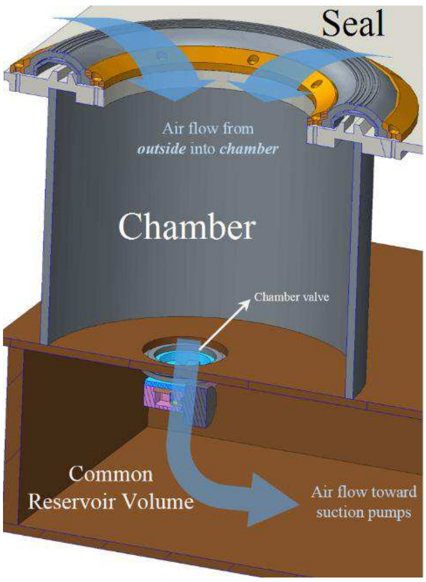

Figure 3: Airflow directions are depicted in CAD model of the suction chamber.

Table 1: Thermodynamic coefficients in equation (1).

Description	notation	value	dimension
Air density	ρ_{air}	1.1883	kg/m^3
Adiabatic exponent	κ_{air}	1.402	
Ambient pressure	p^{amb}	10^5 (1 bar)	pa
Ideal gas constant	R	287.058	J/kgK
Temperature	T_{air}	293.15	$°K$
Chamber Volume	V_{ci}	0.191	m^3

3 CONTROLLER DESIGN FOR SUCTION SYSTEM

Mathematical model of the chamber system is introduced to develop a safe and stable strategy for control of under-pressure inside the chamber.

3.1 Pneumatic Model

In this section we develop a controller for maintaining the desired chamber pressure. The thermodynamic model of the chamber system shown in figure 3 is derived in (Wettach, Hillenbrand, Berns, 2005). The nonlinear state space model is written below.

$$\dot{p}_{c_i} = \kappa_{air} T_{air} R \sqrt{2\,\rho_{air}}\,\frac{1}{V_{ci}} \times \left(A_{Li}\sqrt{p^{amb} - p_{ci}} - A_{Vi}\sqrt{p_{ci} - p_R}\right) \tag{1}$$

In equation (1) the first line depicts the coefficients which are assumed to be constant. Table 1 shows the value and description of each coefficient. All the variables are scalar where p_{ci} is pressure of the chamber i and the only state of the system, $\dot{p}_{ci}$ is its time derivative. p_R and p^{amb} are reservoir and ambient pressures, respectively. The inputs to this system are A_{Li} and A_{vi} which are the leakage area and valve area of the chamber i. The valve area A_{vi} is controlled by chamber valve shown in figure 3 and it adjusts the airflow from chamber to reservoir. That is why in equation (1) its weight is the difference between chamber and reservoir pressure. The same conclusion is valid for chamber and ambient pressure where seal inflation adjusts the air leakage area A_{Li} and also airflow between outside and chamber. The nonlinear system in equation (1) has redundancy in control since it has two inputs and one output.

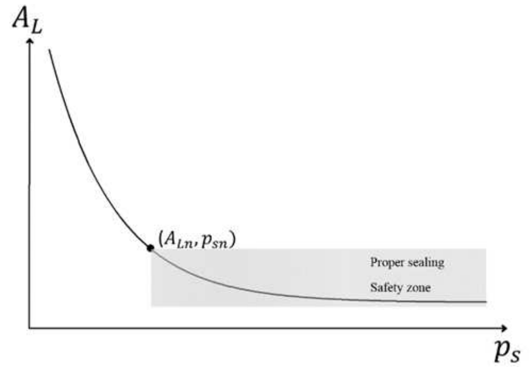

Figure 4: observation based function $A_L = f(p_s)$.The subscript $i$is omitted for simplicity.

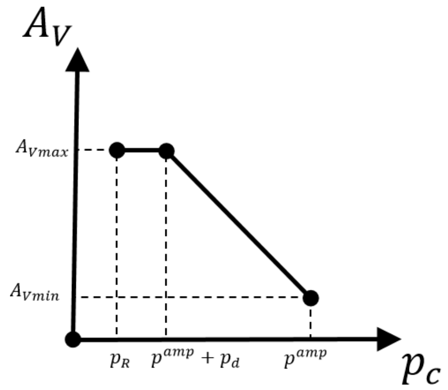

Figure 5: The profile of $A_V - p_c$in controller.

The main challenge arises in the process of seal adjustment. The pressure inside the seal is p_{si}. By increasing p_{si} the seal starts to inflate which normally results in reduction of the air leakage. However the mapping between p_{si} and A_L is completely dependent on the surface of the wall, distance of the seal from wall and the normal force exerted to the seal by the wall. These factors show that the static function $A_{Li} = f(p_{si})$ is strongly coupled with the environment and it is very difficult to precisely model. But according to the observation of the seal behaviour it is obvious that the function $f(.)$ is strictly decreasing and has the profile as shown in figure 4. The main feature of this profile is the knee point (A_{Lni}, p_{sni}) where the slope of the curve decreases when $p_{si} > p_{sni}$ and this region of the profile is a convenient working point for the controller. One main reason is that when $p_{si} < p_{sni}$ the $f(p_{si})$ acts like a large gain (refer to figure 6) which pushes the closed loop poles of the controller toward the imaginary axis and therefore decreases the stability range of the system, moreover f introduces hard nonlinearity to the system. To solve this problem first we have to design the seal in a way that by change in p_s near the knee point, the transition from high slope toward smaller one happens gently (smooth nonlinearity). Second, the controller has to keep the $p_{si} > p_{sni}$ while reaching a stable chamber pressure. In practice we obviously experienced the unstable oscillatory response of the controller when the seal shape is not selected well. Since the focus of this article is on the controller part we do not discuss more on the design of the seal.

3.2 Control Strategy

The objective is to control the chamber pressure p_{ci} by using the inputs p_{si} and A_{Vi}. Apart from the unknown function $f(p_{si})$ in the system other limitations also have to be considered. Each chamber has its own controller to individually set the chamber pressure to the desired value commanded by the higher planner. However, these controllers are not completely independent and the loose coupling between them also introduces constraints in the control design. The reservoir is common source of under-pressure for all the eleven chambers. If one of the chambers loses its under-pressure the pressure inside of the chamber becomes the same as ambient pressure and the reservoir also loses its under-pressure and consequently all other chambers will be effected. In other words, the airflow between chamber and reservoir should be bounded and if it gets more than particular value, the suction pumps no longer will maintain the desired low pressure inside the reservoir. The propagation of high pressure in system is fatal and can result in collapse of robot. Using valve area A_{Vi} the controller can adjust airflow of chamber into reservoir. The last discussion suggests that the controller should not open the valve until it ensures that the leakage area is small and airflow will not change dramatically. The change in A_{Vi} should also be gradual so that even if an unavoidable change is to occur in reservoir pressure it would be so slow that other chambers can track it.

As discussed in the introduction the whole concept of suction system relies on a trade-off between friction and chamber pressure. In order to achieve lower friction the controller should increase the leakage area A_{Li}, this will reduce the chamber under-pressure unless the chamber valve opens completely to compensate for the large leakage area. One possible strategy is to use a profile of figure 5 for A_{Vi}. Rise in chamber under-pressure is the sign of small A_{Li} and therefore controller can take action and rise the A_{Vi} a little bit.

The control scenario is as follows: In phase one the controller acts to *increase* under-pressure from a small value to desired reference p_d. The temporal chamber set point p_{dtemp} initially is an arbitrary predefined ratio of p_{di} for example 10%. The scheduler in figure 6 is responsible to assign the temporal set points. By putting the set point to this value the A_{Vi} also takes a small initial value as computed by the curve depicted in figure 5. Then the PI controller of seal starts to inflate the sealing to reach the temporal set point. When the chamber pressure stabilizes in this set point it means that the point(A_{Li}, p_{si}) has reached the safe region in figure 4 and the leakage area is small enough. In the next step the temporal set point goes up to 20% and accordingly A_{Vi} rises and the controller starts to stabilize itself in new set point. This process continues to gradually push the chamber pressure toward the final desired value.

In phase 2 it is supposed that the phase 1 is completed and the controller has reached a stable point and already made a proper sealing and also A_{Vi} is in maximum value. In this phase the controller track the changes in p_{di} by only adjusting A_{Li}. The PI controller simply takes action and the scheduler puts $p_{di} = p_{dtempi}$ and $A_{Vi} = A_{Vmaxi}$. The seal adjusts itself for lower pressures without any change in A_{Vi}.

In worst case scenario if seal could not reach the knee point due to big leakage on the floor, chamber pressure will never rise and the chamber valve will not be active. This implicit behaviour of the seal eliminates the need for using any higher level activation/deactivation module for the chamber.

In other risky situation, if an active chamber with high under-pressure reaches a hole or obstacle which suddenly enlarges A_{Li} so fast that the controller could not response timely, the chamber will lose under-pressure and the valve area - enforced by profile in figure 5- automatically closes and therefore it will have a very small effect on reservoir and the other chambers.

Despite the fact that the strategy proves to be safe but has the disadvantage of slow response and large steady state time. However when the chamber under-pressure is stabilized the controller is fast enough in tracking desired pressure but remains again slow in response to disturbances.

The chamber pressure control strategy is strongly distributive and each chamber has independent reactional response to obstacles and there is no need for centralized safety check and chamber activation as was proposed by (Schmidt, 2013) and (Kopietz, Schmidt, Schütz and Berns, 2014). It also adds simple safety parameters such as A_{Vmax} and A_{Vmin} to be adapted to the surface and there is no need for complicated safety analysis with numerous safety parameters.

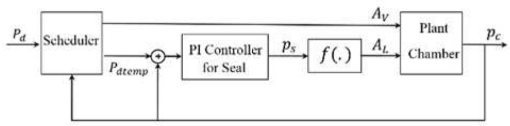

Figure 6: The block diagram of the feedback system.

3.3 Controller and Stability Analysis

Here we investigate the stability of the discussed control strategy. Consider the model in equation (1) for chamber i. We rewrite the model here and drop the sub index i since the whole controller analysis is only for one chamber. The thermodynamic model is as below:

$$\dot{p}_c = k_p(A_L\sqrt{p^{amb} - p_c} - A_V\sqrt{p_c - p_R}) \qquad (2)$$

In equation (2) the constant coefficients of equation (1) is replaced with k_p. We also define new definitions in following equations to make the model description simpler.

$$w_L = \sqrt{p^{amb} - p_c} \geq 0 \qquad (3)$$

$$w_V = \sqrt{p_c - p_R} \quad \geq 0 \qquad (4)$$

$$\gamma(p_c) = A_L\sqrt{p^{amb} - p_c} - A_V\sqrt{p_c - p_R} \qquad (5)$$

Substituting all above definitions in equation (2) yields:

$$\dot{p}_c = \; k_p\,\gamma(p_c) \qquad (6)$$

$\gamma(p_c)$ is a static function of p_c and equation (6) is a simplified version of system dynamics. In order to achieve a desired chamber pressure p_d, the feedback error is defined as:

$$e = p_d - p_c \qquad (7)$$

$$\dot{e} = -\dot{p}_c = -k_p\,\gamma \qquad (8)$$

For a first order system the Lyapunov function V is

$$V = \frac{1}{2}e^2 \qquad (9)$$

According to Lyapunov stability theorem (Khalil, 1996) the nonlinear system in (2) is stable if and only if

$$\frac{dV}{dt} = \dot{V} < 0 \qquad (10)$$

It means that error will decrease over time to its minimal final value, zero. The controller should be designed in a way that $\dot{V}$ remains negative.

$$\dot{V} = \frac{\partial V}{\partial e}\frac{de}{dt} = \frac{\partial V}{\partial e}\dot{e} = e \times -k_p\gamma \tag{11}$$

$$\dot{V} = -k_p\, e\gamma \le 0\ ,\ k_1 > 0 \tag{12}$$

The condition to have negative $\dot{V}$ is that e and γ has the same sign which yields

$$sgn(e) = sgn(\gamma) \tag{13}$$

or

$$\gamma = k_1 e\ \ ,\ k_1 > 0 \tag{14}$$

Where according to new definitions in equations (3-5), γ is:

$$\gamma = A_L w_L - A_V w_V \tag{15}$$

To control the system, γ should have the same sign as e. Considering that w_L and w_V are positive and can be correctly measured, γ can be adjusted using inputs A_L and A_V. However, as it can be seen in equation (16) these two have contrary effects on γ. It is also have to be ensured that the inputs to the system remain positive.

The whole system is stable in the sense of Lyapunov, this means that no matter what the controller inputs are, the chamber pressure is bounded and always remains between P^{amb} and P_R. However, we attempt to design a controller that is asymptotically and exponentially stable if the stability criterion in equation (12) is satisfied.

Now that the stability analysis is provided, It is possible to prove that the strategy in previous section is stable. This strategy has two phases. In first phase, the chamber pressure decreases - under-pressure increases - with a stepwise procedure to approach the desired set point p_d , where it is smaller than current p_c, hence in this phase $e = p_d - p_c < 0$. In each step, the scheduler defines a temporal set point p_{dtemp} and A_{Vtemp}. e is negative and according to equation (14) γ should be negative too. Considering equation (15) and the fact that during each step A_{Vtemp} is constant, the only adjustable input to the system is $A_L = f(p_s)$. As is shown in figure 6 by increasing p_s, A_L decreases until it tends to zero. A PI controller as in equation (17) is implemented to adjust p_s.

$$p_s = -\left(k_p e + k_I \int e.dt\right) \qquad k_p > 0, k_I > 0 \tag{16}$$

Since $e < 0$, PI controller increases p_s until A_L becomes so small that the term $A_V W_V$ in equation (15) dominates and $\gamma < 0$. Now, the trajectory of the system is entered the attraction region of the controller and the stability criterion is valid and hence the controller will converge exponentially to p_{dtemp}.

Of course, at first, the system state is not in the attraction region and system is stable in the sense of Lyapunov but not exponentially. However, we used the model information of equation (15) together with observation model of figure 4 to guide the trajectory toward attraction region. This process is blind since the controller have no information that if there is such an attraction region or not. For example if there is a hole in the wall that the convenient sealing does not take place, inflation of sealing will not help and then the controller can decide that there is an obstacle and it will shut down the chamber.

In phase one, if the robot passes the first step to increase p_{dtemp} then there is a guarantee that the action of sealing is probable - no obstacle - and therefore in next steps the controller will be enough confident to open the A_V more which is risky in the presence of obstacles.

In the second phase of the strategy, the robot already has reached a stable pressure, which yields

$$\dot{e} = -k_{\boldsymbol{p}}\gamma = k_{\boldsymbol{p}}(A_L w_L - A_{Vmax} w_V) \approx 0 \tag{17}$$

Hence, it was assured that the sealing is proper. The most prominent feature of the second phase is that the state trajectory is in attraction region and A_V is kept constant at maximum. The controller start to track the reference values by only adjusting the seal. Since the sealing process is finished and the state trajectory is already inside the attraction region – equation (12) is balanced - the controller response is swift and fast.

4 IMPLEMENTATION RESULTS

The controller is implemented on a digital signal processing (DSP) device with the sampling rate of 100 Hz. All the sensory data from the pressure sensors of reservoir, chambers and seals are connected to DSP. Actuators for chamber valve servomotor and seal pressure switches are also commanded by the same DSP. In the following results the leakage area (A_L) and valve area (A_V) are normalized by A_{Vmax}. The normalized values $\overline{A_V}$, $\overline{A_L}$ are calculated by the following equations.

$$\overline{A_V} = \frac{A_V}{A_{Vmax}} \tag{18}$$

$$\overline{A_L} = \frac{A_L}{A_{Vmax}} \tag{19}$$

The step response of the control strategy in phase one is depicted in figure 7. In this experiment the $\bar{A}_{Vmin}$ is 0.3. The seal starts to inflate until it

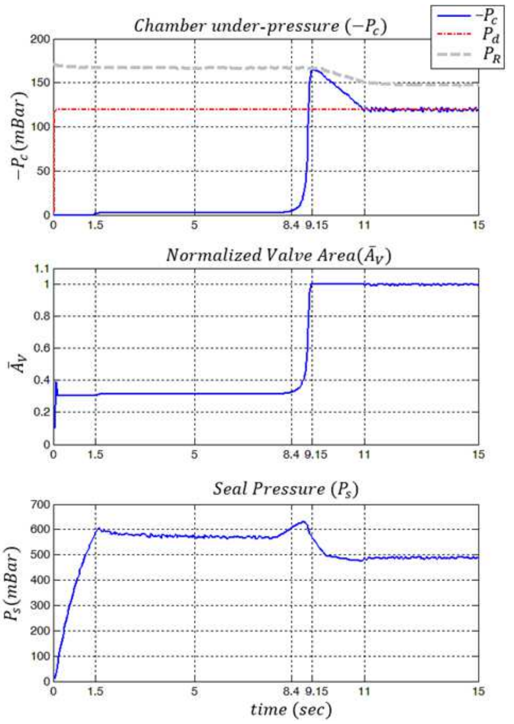

Figure 7: Step Response of the controller in phase 1.

reaches the wall surface at $t = 1.5s$. Afterwards, the chamber pressure slowly increases until $t = 8.4s$. During this interval the controller conservatively start to open A_V until at $t = 8.4s$ perfect seal happens and chamber pressure suddenly increases. A_V takes the same profile as P_c since they are linearly dependent as shown in figure 5. Consequently, the PI controller adjusts P_s to reach desired pressure value (p_d). The main feature of this response is that the reservoir pressure (P_R) changes smoothly and has no fluctuations. The controller is not designed to have fast response since in the case of climbing robot, safety is the main design criterion where the controller managed to achieve such a satisfactory safe response by suppressing the airflow inside the chamber. The controller opens valve only when that it is assured the leakage area is small. One of the advantages of this method is that no exact model of the system is used to estimate airflow and the controller manages to adjust the airflow by only observing the behavior of the system.

The controller also achieved the smallest steady-state seal pressure. In order to have small interaction between seal and wall or minimum friction, the seal pressure should be as small as possible. As shown in figure 7, at $t = 1.5s$ the seal reach the surface at $P_s = 600\,mBar$, however eventually it settles down at $t = 11s$ at 500 $mBar$, which provides the lowest possible normal force and friction on the wall.

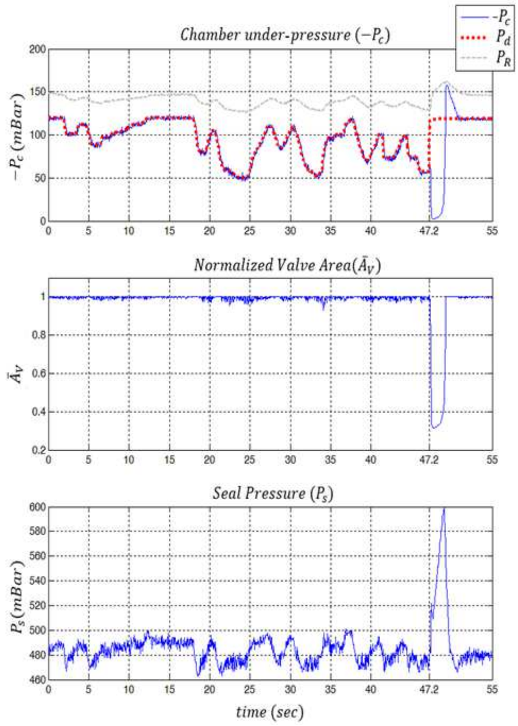

Figure 8: The tracking response of the controller in phase 2.

The tracking response of the controller is shown in figure 8. In this case, the controller works in phase 2. It is able to follow arbitrary desired signal with acceptable precession of 3 mBar. As we discussed, since in this phase the state trajectory is already in attraction region, the response is swift and stable. However at time $t =$ 47.2s a very abrupt change occurred in desired signal that the controller were unable to follow and therefore chamber under-pressure is lost. In this situation adhesive force decreases which is considered highly risky. However, as soon as the under-pressure drops, the controller closes A_V and preserves the reservoir pressure.

One of the important assumptions in the design of the controller is to assume that the curve shown in figure 4 is valid throughout the experiment. This curve is a simplified model of the controller interaction with the environment (wall). The controller is valid if the function $A_L = f(p_s)$ is strictly decreasing. In figure 9, the identification data is depicting the function $f(p_s)$. The data gathered under the condition of stable chamber pressure and in fact shows the working points of the controller in steady-state. As it can be seen in the figure, the concentration of the points are around knee of the curve which is a testimony to the analysis given in section 3.1.

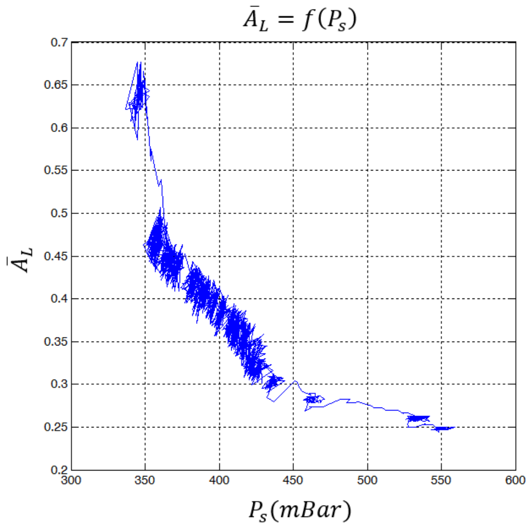

Figure 9: Identification data of the seal behaviour under the condition of stable chamber pressure.

5 CONCLUSION

This paper reports the design procedure of a nonlinear controller for the chamber pressure of the climbing robot CREA. The controller not only moves toward a stable attraction region but also satisfy rigorous conditions of safety. In previous works the safety issue is included in the path planning high level control which administrates the overall behaviour of several chambers and decides according to the predefined safety measures. Many parameters are defined for safety measures and the response of the system is slow since the process is high level. In this paper we incorporated reactional safety features directly into the stability of the system. Important feature of the system is that the equilibrium of the controller is dependent on the environment (wall surface). The controller observes and interacts with environment to determine the equilibrium and then moves towards the attraction region. If the controller could not find equilibrium, it will continue to search without putting robot at risk. Its response is reactional and fast especially in risky situations to guarantee safety. The controller is very simple to implement in low level DSP to increase the sampling rate. It also considerably reduces the burden on high level planner since the control strategy is designed in a way that the chambers work highly distributive.

However, there are some open questions that need to be investigated. One is the assumption of the function $A_L = f(p_s)$. This assumption is valid in working on common concrete walls but there are some specific situations like the existence of relatively big steps on the wall that have different leakage profile. In this cases high level planner should be involved in overall decision making process. We are also working on a better design for seal to improve the behaviour of the sealing process. It is also desirable to develop estimation and learning methods for friction, force and coordination of different chambers because of the strong coupling with environment.

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