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The Variable Boundary Layer Sliding Mode Control: A Safe and Performant Control for Compliant Joint Manipulators

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***Abstract*—The control of compliant joint manipulators is challenging for two reasons. First, the elastic elements of the compliant actuators can store an important amount of energy which can be potentially dangerous and needs therefore to be controlled. Second, the compliance introduces nonlinearities and uncertainties in the system. In this paper, we propose a new control scheme, the Variable Boundary layer Sliding Mode Control (VBSMC) for a safe and performant control of compliant joint manipulators. The control method allows achieving various interaction levels while maintaining good performances. This is realized by adjusting the torque limit parameter and the expanding factor of the controller. Tests have been carried on the collaborative robot Baxter in order to compare the performances and the safe behaviour of the VBSMC with the internal controller of the robot. Results show that the VBSMC exhibits either similar or higher performances than the robot controller and can achieve different interaction levels.**

***Index Terms*—safe, performant, compliant joint manipulator, sliding mode control, variable boundary layer**

I. Introduction

Industrial robots, nowadays, are typically heavy machines separated from the human workers by cages [1]. They are programmed to work autonomously and perform repetitive and dangerous tasks. However, the automation of unstructured tasks (e.g. in an unknown environment) by industrial robots is either very difficult to implement or too expensive. Also, the reprogramming of the robot requires a highly trained specialist and is time consuming [2]. Recently, there is a strong trend in the research community and industry [3] which points to the use of collaborative robots. These robots are cage-free, cheap and easily reprogrammable and are seen as a way to close the gap of using robots under a master slave paradigm and bring them closer to humans as coworkers. The idea is to cooperate with the human worker and combine his skills, namely dexterity, flexibility and problem-solving ability with the strength, endurance and precision of the robot [4]. The collaborative robots show all their advantages in Small and Medium Companies (SMEs) which cannot afford expensive industrial robots and where the variability of the tasks is more pronounced. Since they do not need a cage and safety equipments, they can be moved easily from one location to another location in the factory and reprogrammed for a new task.

For a safe Human Robot Interaction (HRI), robotic manipulators are often actuated by compliant actuators [5] [6] [7]. However, the elastic elements of the actuators can store an important amount of energy which can be potentially dangerous and therefore needs an extra safety layer which is generally implemented in software by means of a compliant controller designed for safe HRI [8]. A typical example is the case where the robot joint is deviated from its reference position. Traditional PID controllers usually used in industrial robots for fast accurate trajectory tracking, are not designed to be intrinsically safe but rather precise and good at disturbance rejection. This is accomplished by using high PID gains which translates in strong, fast and potentially unsafe responses to deviations in position errors. The control of compliant joint robots using different approaches has been widely studied [9] [10]. A commonly used safe control method for mechanical systems is the impedance control [11]. The mechanical impedance is the relationship between the motion and the force of the end-point effector. Introduced first by Hogan [12] in the robotics field, it allows to maintain the human-robot interaction force under safe levels [13]. In [14], a high impedance value is used to control a robotic manipulator for a precise motion. However, the adoption of such control scheme with high impedance gains can suppress the intrinsic compliance and generate dangerous motions. The choice of the impedance value is thus a trade off between safety and tracking performance.

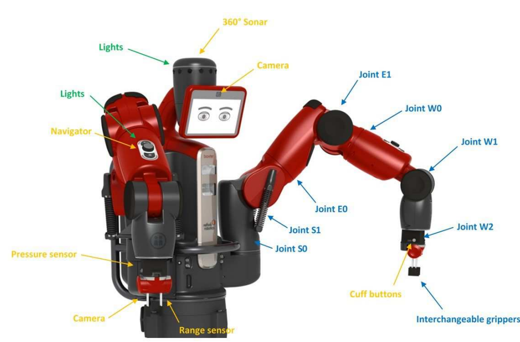

Fig. 1. The Baxter robot developed by Rethink Robotics™ and its main components

The Proxy-based Sliding Mode Control (PSMC) is another safe control method [15]. This was studied for enhanced physical interaction of an anthropomorphic compliant arm in [16] and employed for a pneumatic manipulator [17] and a bionic knee exoskeleton [18]. The PSMC achieves a responsive and accurate PID-like tracking during normal operation with

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a slow and safe recovery from large deviations from the target position. In practice, the system to be controlled as well as its model are always uncertain or and sometimes mostly unknown. This is particularly true in the case of compliant joint manipulators where the elastic elements introduces nonlinearities and uncertainties in the system. Although the PSMC controller is based on the Sliding Mode Controller (SMC), its PID component makes it less suitable for the control of nonlinear system and decreases the robustness of the controller. Therefore, the SMC was chosen as the basis of the developed method for a safe and robust control.

This paper presents a novel controller, the Variable Boundary layer SMC (VBSMC) for a safe and performant control. By adjusting the torque limit parameter and the expanding factor of the variable boundary layer, different levels of interaction can be achieved while maintaining good tracking performances. The experiments are performed on the collaborative robot Baxter [19]. The robot is composed of two 7-degree-of-freedom arms incorporated with force, position and velocity sensing. The robot is an adequate platform for testing the controller since it is actuated by compliant actuators, namely Series Elastic Actuators (SEAs). The paper is organized as follows. Section 2 presents in detail the VBSMC control scheme with an introduction about the SMC and the method to eliminate chattering. The proposed control method is then verified through experimental results in section 3. Section 4 discusses the controller and future improvements.

II. VBSMC

The Sliding Mode Control (SMC) is a nonlinear and discontinuous controller [20]. The strength of the SMC lies in its robustness with respect to system uncertainties [21]. The method changes the dynamics of the controlled system through a discontinuous state-feedback control law. Based on the position of the system in the state space, a different continuous structure is used and forces the system to slide along the so-called sliding surface.

The output command, in the case of a torque-controlled joint, with position and speed measurements can be written as follows

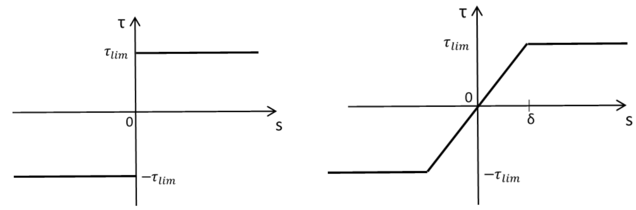
$$\tau = \tau_{lim} sgn(s) \tag{1}$$

$$s = (\theta_d - \theta) + \lambda(\dot{\theta}_d - \dot{\theta}) \tag{2}$$

$$sgn(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \tag{3}$$

where τ is the commanded torque, τ_{lim} is the torque limit, sgn is the signum function, s is the system's state, θ_d is the desired position, θ is the joint position, λ is the convergence time constant, $\dot{\theta}_d$ is the desired speed, $\dot{\theta}$ is the joint speed.

Once the sliding surface $s = 0$ is reached, the system converges exponentially to the stable origin ($\theta = \theta_d$, $\dot{\theta} = \dot{\theta}_d$) with a speed proportional to the convergence time constant λ (see equation II).



(a) Without a boundary layer (b) With a boundary layer

Fig. 3. Torque command as function of system state

The use of a signum function creates, however, a high frequency oscillation around the sliding surface. This is called the chattering phenomenon. Different solutions have been proposed to the chattering problem. Among them, one can cite the low-pass filtering of the control signal [22] and the use of a high order sliding mode control [23]. One of the most common methods is the boundary layer approach [24]. It consists in using a continuous function instead of a discontinuous control law, namely a saturation function (Figure 3.b).

$$sat(s) = \begin{cases} 1 & s > \delta \\ \frac{s}{\delta} & -\delta \leq s \leq \delta \\ -1 & s < -\delta \end{cases} \tag{4}$$

where δ is the width of the boundary layer.

The core component of the VBSMC is a SMC controller with a boundary layer as shown in Figure 5. The tracking performance of the controller is set by tuning the τ_{lim} parameter and the width δ of the boundary layer. The τ_{lim} parameter allows also to set a limit on the applied torque to ensure a safe interaction with the human.

The width of the boundary layer is directly linked to the tracking accuracy of the controller. Indeed, in the case of a large boundary layer, the linear part of the output command (see Figure 3.b) exhibits a small slope. This can be compared to a proportional regulator with a low K_p gain. In order to achieve a good tracking accuracy, a thin boundary layer has been chosen. This, however, leads to a response close to the signum command depicted in Figure 3.a and therefore creates chattering.

Moreover, the noise on the measured speed is contributing to the chattering when the system state is close to the sliding surface $s = 0$. Indeed, in the case of a nonzero convergence time constant λ and a thin boundary layer, the speed noise leads to an output torque jumping between $-\tau_{lim}$ and τ_{lim} as in a bang bang controller (see equations II). Therefore, the convergence time constant is set to zero and a K_D gain is inserted in the control scheme to damp the response (see Figure 5).

Another phenomenon observed during the control of the robot's arm is a backlash-like behavior of certain joints at specific positions. This is probably due to dead zones at the joint level where the springs don't act. This leads to local high dynamics in the joint space. In order to counter this effect, additional damping is needed. However, increasing the damping term K_D is limited because of the noise on the

(a) PID (b) VBSMC

Fig. 2. Experiments with Baxter where the applied torque is tested for both the PID controller and the VBSMC. In the case of the internal controller, the robot's arm can be stopped by applying a relatively high force with the full hand while with the VBSMC, the robot can be stopped with a single finger. Link: https://youtu.be/IArLYxqxMaI

measured speed. This can be overcome by using a variable boundary layer. The idea is to adjust the slope of the saturation function in function of the measured speed by modifying the width of the boundary layer as shown in Figure 4, introducing in this way an effect similar to a damping.

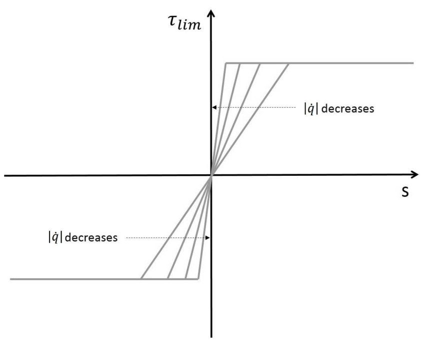


Fig. 4. Output command in function of system state s for a variable boundary layer SMC.

The boundary layer is made variable in function of the measured speed as follows.

$$\delta(\dot{q}) = \delta_0 \left(1 + \alpha|\dot{q}|\right) \quad (5)$$

where $\delta(\dot{q})$ is the variable boundary layer width, δ_0 is the boundary layer width at zero speed and α is the expanding factor.

Note that, when using a variable boundary layer, unlike the damping by a K_D gain, the noise on the measured speed is not reflected to the output torque when damping the system with a variable boundary layer. Indeed, consider the robot arm at rest at a certain desired position q_d ($s = 0$) with a nonzero speed noise. The latter will create an expansion of the boundary layer according to equation II but no torque will be produced since $s = 0$.

The variable boundary layer $\delta(\dot{q})$ is shown in Figure 5 as an input parameter of the SMC block. In order to improve the robot's steady state error during trajectory tracking, an integral gain K_I is used. An anti-windup block is also inserted in the control scheme to limit the corresponding torque. Finally an additional saturation block is added to limit the total torque applied to the robot joints to safe values.

The commanded torque reads as

$$\tau = sat(\tau_{lim} sat(s) + sat(K_I \int (q_d - q)\, dt) + K_D(\dot{q}_d - \dot{q})) + \tau_g \quad (6)$$

where τ_g is the gravity compensation torque computed by the robot.

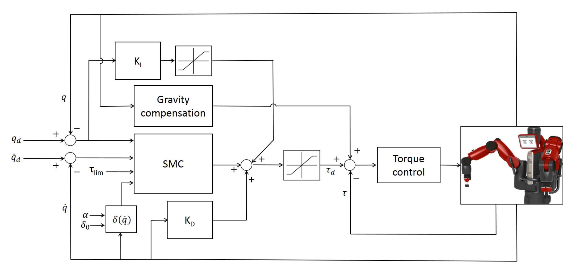


Fig. 5. VBSMC control scheme. The core component of the controller is a SMC with a variable boundary layer. A K_D gain is used in place of the convergence time constant λ of the SMC to damp the system's response. In order to improve the trajectory tracking accuracy, an integral gain K_I is added in the control scheme.

III. Experiments

A. Implementation

The VBSMC controller is implemented in Baxter by feeding the calculated torque to the internal torque controller and as such bypass the default position control of the robot. The Robot Operating System (ROS) is used as the main software framework. The control frequency of the joint control boards is 1 kHz. The control method is implemented on the left arm of the robot and its parameters (τ_{lim}, δ, K_D, etc) are first tuned for a single joint (shoulder joint s0 - see Figure 1) and gradually for the other joints.

B. Performance evaluation

This section presents tests performed both on a single joint and multi-joints level to evaluate the performance of the controller. The results are compared with the internal PID controller of the robot.

1) One joint: Step responses of the VBSMC controller for a single joint (shoulder joint of left arm) and different values of τ_{lim} are shown in Figure 7.a. As it can be observed, the PID controller exhibits high torques ($\pm 15\,Nm$) and high speed ($1.5\,m/s$). For what regard the position response, at $\tau_{lim} = 7\,Nm$, both controllers reach the desired position at the same time but the VBSMC controller creates less overshoot. By changing the torque limit parameter, it is possible to achieve different safety levels. One can see that the rising time of the curves vary but the settling time are approximately the same. Figure 6 depicts the tracking of a sinusoidal trajectory of the first joint of the left arm (left s0) for the two controllers. The VBSMC controller, unlike the PID controller, tracks the reference trajectory without overshoot.

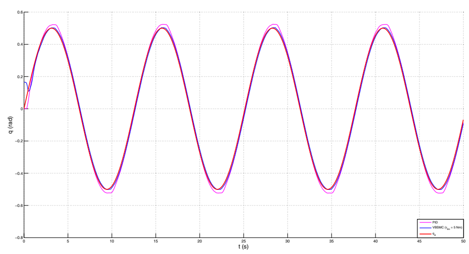


Fig. 6. Tracking of a sinusoidal trajectory (left s0) by the internal PID controller (RMSE = 2.25e-2 rad) and the VBSMC controller (RMSE = 2.06e-2 rad). The PID regulator exhibits an overshoot with respect to the sinusoidal reference.

2) Multiple joints: In order to evaluate the precision of the controller on a multi-joint level, a positioning test in the task space has been performed where a desired position is prescribed to the robot end-effector. The robot arm starts at the same position for both controllers (internal PID and VBSMC) and after a defined timeout, the final end-effector positions are saved. This is executed 5 times. Figure 8 shows the obtained results. The PID controller shows an accuracy slightly higher ($\pm 1mm$) and a better repeatability. Note, however, that the number of trials is probably not high enough to conclude about the repeatability of the controller.

Trajectory tracking tests have also been performed. Figure 9.a and 9.b show the end-effector of Baxters left arm tracking a circular trajectory, this is realized respectively by the internal PID and the VBSMC controllers. Although the end-effector trajectory, when controlled with the VBSMC, differs at some locations from the circular trajectory, a better overall tracking accuracy is observed compared to the trajectory exhibited by the robot when controlled by the internal PID controller. The latter shows an overall constant error (end-effector positions describe a larger circle).

C. Safety evaluation

This section presents tests performed on Baxter to evaluate the safe behavior of the VBSMC controller when varying the torque limit and expanding factor parameters. This is

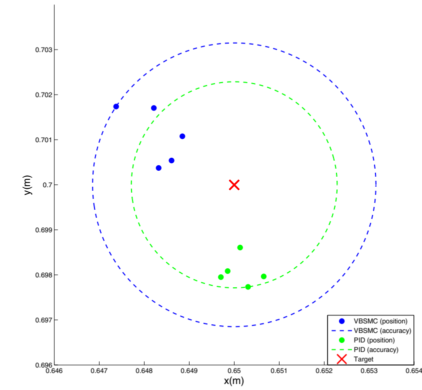
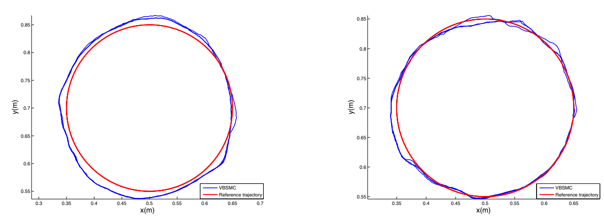


Fig. 8. Positioning tests in the task spacewhere the end-effector is controlled to reach the target position (red cross). The circles indicate the distance of the farthest point with respect to the target. The end-effector starts at position : (x = 0.7, y = 0.3, z = -0.2) m and its position is registered after 7 sec of timeout.



(a) Internal controller

(b) VBSMC

Fig. 9. End-effector tracking of a circular trajectory by the internal PID controller (RMSE = 1.77e-2 m) and the VBSMC (RMSE = 1.12e-2 m)

compared with the internal PID controller of the robot.

In this test, the shoulder joint of the left arm of Baxter is set at a specific position, a disturbance (deviation from the reference position) is then applied manually. Figure 10 shows the recovery responses for different torque limits. The VBSMC makes the arm move slowly and safely to the reference position thanks to the limitation on the torque. One can see that the PID controller exhibits a quick and unsafe motion to the reference trajectory (with overshoot). By decreasing the torque limit, it is possible to decrease the convergence speed to the reference position and obtain a slower motion. This however at the expense of a lower tracking accuracy at low torques. Therefore another method is investigated to decouple the damping in the system and the input torque.

As shown in Figure 11, varying the expanding factor of the variable boundary layer allows adding damping in the system and therefore achieving a safe behaviour. Another advantage of varying such parameter, is that the torque limit stays unchanged (see torque curves of Figure 11). Therefore, it is possible to control independently the convergence behavior of the robot (expanding factor) and the interaction forces (torque limit).

IV. CONCLUSION

The experimental results showed that the VBSMC is an adequate method to control a compliant joint manipulator, in this case the Baxter robot, for a safe human robot interaction. For what regard the performances, the VBSMC performs equivalently (e.g. point-to-point task) or better than the internal controller of the robot (e.g. single joint control and trajectory control). During the experiment, the same set of parameters was used for the different tests. A possible option to reach higher performances would be e.g. to use different parameter sets for a point-to-point task and trajectory tracking task.

By varying the torque limit, it is possible to reach various safety levels in terms of interaction forces. In order to achieve motions with a very slow convergence, a low torque limit is needed. This leads to lower performances. The expanding factor of the variable boundary layer is therefore used to set the convergence behavior of the robot independently from the force interaction levels.

In terms of safety and performances, the VBSMC performs overall well. Thanks to the variable boundary layer, the chattering is eliminated. Another interesting aspect of the VBSMC lies in its energy efficiency, i.e. reduced control effort. However, the controller requires a fine tuning of its parameters, more particularly to avoid chattering. A possible improvement would be to implement an adaptive filter setting the parameters of the controller to an optimal set (e.g. maximum performance/minimum chattering).

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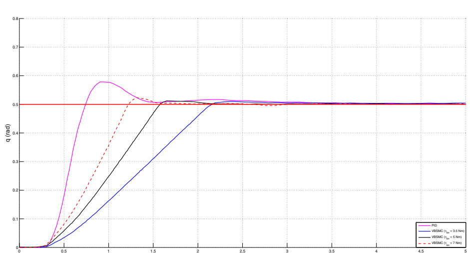
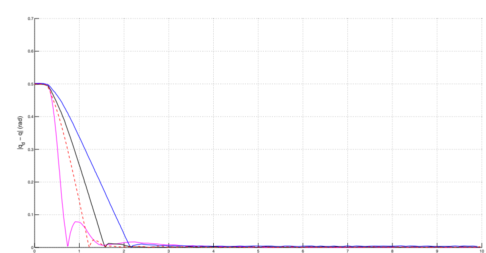
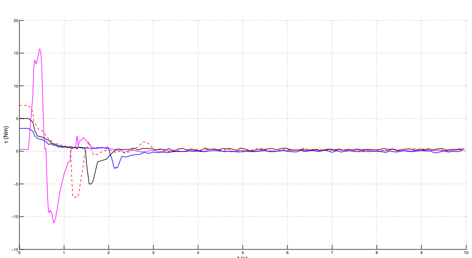


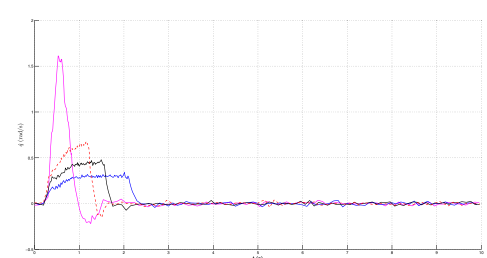
(a) Position (rad)



(b) Absolute error (rad)



(c) Torque (Nm)



(d) Speed (rad/s)

Fig. 7. Position, absolute error, commanded torque and speed (joint left s0) of the VBSMC controller and the internal PID controller of Baxter with different torque limits. The PID controller creates an overshoot on the joint angle. The latter exhibits relatively high torque and speed.

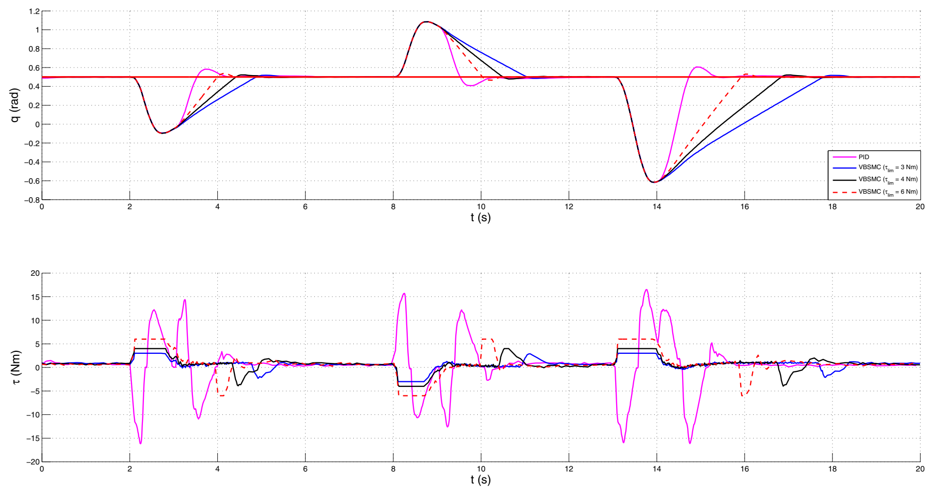


Fig. 10. Disturbance test with different torque limits τ_{lim} - Position (rad) and torque (Nm) of the shoulder joint *left s0*. Slower responses are achieved by decreasing the torque limit parameter.

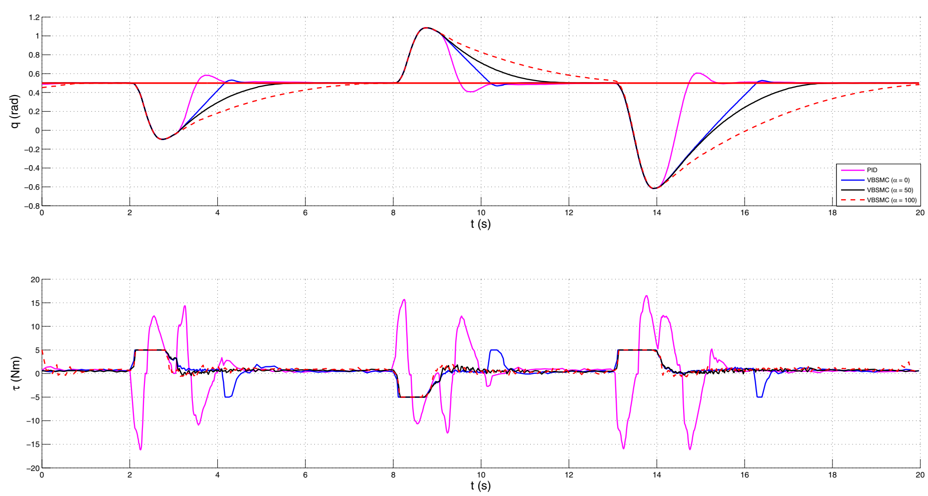


Fig. 11. Disturbance test with different expanding factor α - Position (rad) and torque (Nm) of the shoulder joint *left s0*. Slower responses are achieved by decreasing the expanding factor parameter. The torque limit stays unchanged.

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