Collaborative Welding and Joint Sealing Robots With Haptic Feedback

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Abstract -
Due to their unstructured and dynamic nature, construction sites present many challenges for robotic automation of tasks. Integrating human-robot collaboration (HRC) is critical for task success and implementation feasibility. This is particularly important for contact-rich tasks and other complex scenarios which require a level of reasoning that cannot be accomplished by a fully autonomous robot. Currently, many solutions rely on precise teleoperation that requires one operator per robot. Alternatively, one operator may oversee several semi-autonomous robots. However, the operators do not have the sensory feedback needed to adequately leverage their expertise and craftsmanship. Haptic interfaces allow for intuitive human-robot collaboration by providing rich contact feedback. This paper presents two human-robot collaboration solutions for welding and joint sealing through the use of a haptic device. Our approach allows for seamless transitions between autonomous robot capabilities and human intervention with rich contact feedback. Additionally, this work opens the door to intuitive programming of new tasks through haptic human demonstration.

Keywords -

Robotics; Construction; Haptics; Human-Robot Collaboration; Robotic Manipulation; Tactile Feedback.

Figure 1: Robotic solution to a welding task combining robot autonomy and haptic human intervention. Video of task execution: video. Source code can be found here: Project GitHub.

1 Introduction

In recent years, progress in mobility, manipulation skills, and AI reasoning have started to enable the use of robots in space, underwater, homes, agriculture, and construction [1]. A particularly important area of interest is the automation of dangerous, strenuous, and labor-intensive tasks [2].

Construction sites are especially challenging environments for autonomous robots because of their highly unpredictable and unstructured nature [3, 4]. Hence, fully autonomous robots that replace human labor are not the most feasible or ideal solution. The majority of current approaches rely on a human operator that oversees a single-task autonomous robot. The operator receives only visual feedback and is limited in the type of input and recovery from failure he can provide due to the lack of an intuitive interface to do so. [4] attributed this lack in technical flexibility of construction robots to the fact that early construction solutions imitated systems initially developed for industrial fabrication [5].

Some tasks are structured enough to be autonomously performed by a robot with little human input, but many require a more flexible approach that incorporates a higher degree of human reasoning and intuition [6]. Given this reality, a method to design construction robots should be flexible enough to allow varying levels of human-robot collaboration depending on the task.

Haptic devices (Fig.1) provide an effective interface for collaboration by allowing the human to (1) feel the contact forces between the robot's end-effector and the environment [7], and (2) easily intervene and control the robot motion in scenarios that the autonomous behaviors are not able to handle successfully [8]. Additionally, data from these haptic interventions can be collected and used to learn new autonomous skills. Remote robot control using a haptic interface has been tested in fields such as surgery [9] and underwater exploration [1], but has not yet been widely implemented in construction.

In previous work, the authors explored human-robot collaboration solutions to five hazardous and repetitive construction tasks: installing drywall, painting, bolting, welding, and sealing precast concrete slab joints [10]. Our industry partner, Goldbeck, was interested in automating these assembly and finishing tasks that require on-site, repetitive manual effort, ergonomically challenging positions, and working from dangerous heights. [10] outlines a method for designing collaborative robotic solutions with haptic feedback and to assess their feasibility in simulation.

In this paper, we focus on two of the previously explored tasks (steel welding and sealing precast concrete joints) and apply the aforementioned method to design more flexible collaborative solutions. Different from [10], we propose relying primarily on the robot's functional autonomy and using haptics as an effective and intuitive way to intervene in unexplored or failure scenarios. Force data from the recovery strategy employed by the operator can be recorded and used to learn from demonstration and augment the robot's autonomy. Over time, the robot will require less human intervention. This higher degree of autonomy could allow a single operator to supervise many robots at once, overcoming the problems of teleoperation in which one operator per robot is needed.

2 Related Work

While factories have typically separated workers from robots due to safety concerns, human-robot collaboration cannot be overlooked in construction, as robots and humans share one workspace [2]. This requires devising solutions that allow us to effectively combine the workers' expertise with the robots' autonomous skills.

Construction literature has studied the use of teleoperation devices [11, 12, 7], particularly focusing on construction machinery, such as excavators. These solutions often involve cameras for visual feedback and GPS sensors for navigation, which can be sufficient to accomplish low dexterity tasks with increased operator safety. However, [7] states that complex tasks involving contact greatly benefit from additional sensory feedback such as tactile information. Furthermore, teleoperation solutions rely heavily on the operator's guidance and do not fully exploit the autonomous capabilities of the robot.

A different set of collaborative solutions currently used onsite have semi-autonomous robots with a human supervisor that oversees the tasks such as drywall installation, concrete drilling, and layout [13]. The supervisor can provide simple inputs to the robot, such as when to start or stop the operation, while the robot handles the rest of the task. This approach makes better use of modern robotics capabilities and allows a single operator to manage several robots. However, the interfaces used to provide inputs to the robot are often too simplistic to allow recovery from failure.

In the event of a robot failure during task execution, joysticks and control pendants do not always provide enough feedback for the operator to intervene in an effective way that enables timely task completion. Additionally, there is currently no streamlined way to learn from the operator's intervention and use this data to improve the robot's autonomous capabilities.

By allowing the operator to feel the contact between the robot and its environment, haptic devices increase the range of scenarios in which the operator can aid in failure recovery [14]. Additionally, we can easily record both force and position data during the operator's intervention. These human demonstrations of recovery strategies can allow the robot to learn new skills [15] and augment its functional autonomy.

Haptic devices have been used by the construction industry in combination with virtual reality for task training purposes [16]. The technology has allowed workers to train in a safe environment with realistic task conditions. However, haptics are still a novel technology in construction applications and field use has not been reported.

Current algorithms for haptic control of robots [17] can handle large communication delays, making them effective interfaces for remote intervention at long distances. In [1] an operator haptically controls an underwater ocean exploration robot from a distance of $100m$.

Finally, [18] provides an example that integrates two modalities of robot control: autonomous robot behavior and expert human-guided motion interactions. In this study, a group of mobile robot arms successfully installed drywall boards in simulation with flexible human intervention.

This body of prior work illustrates how keeping the human in the loop with adequate feedback can facilitate successful task automation in complex, unstructured environments. Moreover, it highlights the value of haptics as a way to provide a flexible and effective interface for human-robot collaboration as well as teaching robots new autonomous skills.

3 Methods

This section explains how we designed our collaborative solutions as well as the framework used to implement the haptic controls. Additionally, we tackle the issue of reduced workspaces, which is often challenge when using a portable haptic device.

3.1 Four-Step HRC Design Method

In order to develop the HRC welding and concrete sealing solutions presented in this paper, we built on a method previously developed for designing collaborative robotic solutions with haptic feedback [10].

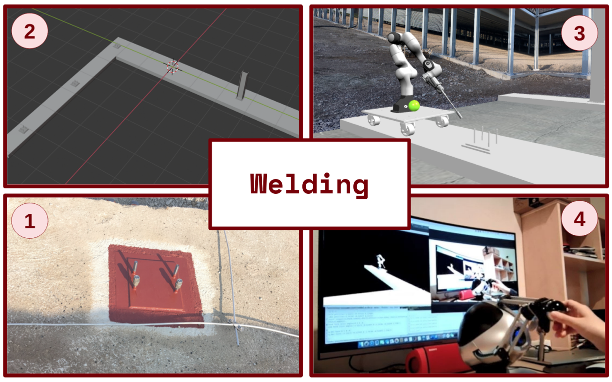

Figure 2: Perimeter welding on anchor plates four-step method: (1) collect data, (2) generate simulation environment (3) simulate autonomous behaviors, (4) allow for haptic intervention.

In this paper we focus on using autonomous behaviors whenever possible and using haptics only for failure recovery or demonstrating new skills. In summary, the improved method involves: (1) collecting production data of the manual approach onsite, (2) generating a realistic simulation based on the Building Information Model (BIM) data provided by the industry partner at Level of Development 300, (3) generating autonomous behaviors that allow the robot to interact with the environment in simulation, (4) establishing a flexible control framework that allows for seamless haptic intervention when needed.

For step three we used SAI, an open-source simulator developed by the Stanford Robotics Lab in collaboration with Google [19] to control robots in physically realistic virtual environments. Its modules include a control library with the Operational Space formulation and a dynamics engine that can simulate multiple contacts between robot bodies and the environment [20].

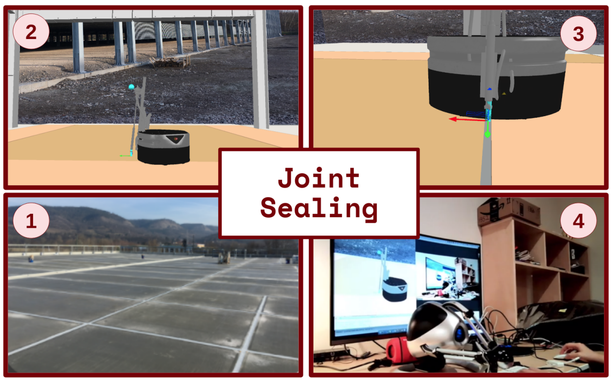

Figure 3: Concrete joint sealing four-step method: (1) collect data, (2) generate simulation environment (3) simulate autonomous behaviors, (4) allow for haptic intervention.

3.2 Haptic Simulation and Controls

We implemented a flexible state machine that enables switching between an autonomous mode where the robot executes the required behaviors to complete the task without human intervention, and a haptic mode where an operator can take over and intuitively control the robot end-effector pose while feeling its interaction with the environment. The haptic mode records contact and position data from the operator demonstration, which can then be used to learn new autonomous behaviors.

SAI allowed us to quickly incorporate industry feedback in simulation and iterate through multiple robot designs before converging to a final solution. The simulations considered factors such as friction, object collisions, and system non-linearities. This functionality allowed for a realistic consideration of the construction environment and its constraints.

In order to generate autonomous behaviors, we used the operational space formulation [18] which allows us to describe the equations of motion of a robot at a desired control point. Let the robot have a task to fulfill, described by the task Jacobian J_t, the task coordinates x_t, and the associated task velocity $\dot{x}_t$, such that $\dot{x}_t = J_t \dot{q}$, where q represents the robot generalized coordinates and $\dot{q}$ represents the robot generalized velocities. The equation of motion of the robot in free space is:

$$M(q)\ddot{q} + b(q, \dot{q}) + g(q) = \Gamma \quad (1)$$

where $M(q)$ is the robot mass matrix, $b(q, \dot{q})$ represents the Coriolis and centrifugal forces, $g(q)$ is the robot gravity vector, and Γ is the motor torques. In the following, we will drop the dependencies in q and $\dot{q}$ for better readability.

After multiplying eq.(1) by the dynamically consistent generalized inverse of the Jacobian, $\bar{J}_t$, we get the operational space equation of motion:

$$\Lambda_t \ddot{x}_t + \mu_t + p_t = F_t \quad (2)$$

where $\mu_t = \bar{J}_t^T b - \dot{J}_t \dot{q}$ is the task space Coriolis and centrifugal, and $p_t = \bar{J}_t^T g$ is the gravity projected onto the task space. The task control torques will then be $\Gamma_t = J_t^T F_t$.

Section 3.3 explains how we implemented the haptic controller for our Falcon Haptic device which has a very limited workspace using the operational space formulation.

3.3 Haptic Workspace Extension

Exploring a large virtual environment using a haptic device with limited workspace capability is challenging. The user will easily reach the physical limits of the haptic device's workspace. Similar to the approach proposed by

[21], we use a lock mechanism to hold the robot position while the human adjusts the haptic device joystick [22]. The red dashed box represents the original workspace before the lock mechanism and the green box represents the new explorable workspace of the robot after the lock mechanism. The new explorable workspace is based on an offset defined by the distance from the new haptic device position to the held end-effector position (Fig. 4).

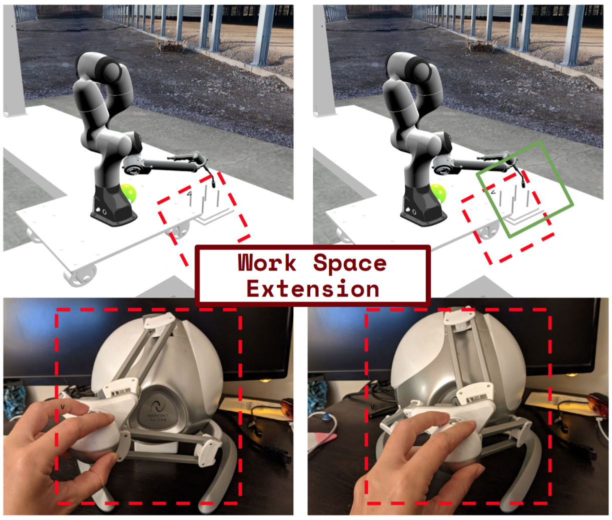

Figure 4: Work space extension: the robot position is held constant while the operator adjusts the haptic device to continue exploring the robot workspace.

Therefore, the desired position in cartisian space is given by:

$$x_t = x_{hold} + \eta x_{haptics} \tag{3}$$

where x_{hold} is the position of the end-effector before entering the haptics state, $x_{haptics}$ is the raw value read from the haptic device, η is a scaling hyperparameter, x_t is the desired end-effector position in equation 2, which is then used to compute the required joint torques.

4 Task Descriptions

The task data for welding and joint sealing was collected from a six-level prefabricated parking structure in Germany (Fig. 5). This section describes the traditional process to complete both tasks in the field and identifies specific requirements for automation with field robots.

4.1 Welding

Each parking structure requires welding 144 anchor plates to the foundation. These anchor plates are the support of the structural steel columns that span all six levels. Given the structural importance of the joint between the columns and the foundations, field welding is a sensitive task that requires high expertise and slow, repetitive manual work. The task consists of three key steps: placing the anchor on the foundation, welding two opposite corner points to fix the anchor position, and welding the perimeter of the anchor (Table 1).

Table 1: Welding production performance

Welding	Prod. (min/u)	Total (h)	Prep./day (h)	Workers
Place	0.5	1.2	0	1
Fix	15	36	2	1
Weld	45	108	0.2	1

Automating this welding task requires mobility and a robotic arm with a welding torch end-effector. In this paper, we developed a simulation using a 7-DOF Panda arm with a welding torch on a mobile platform (Fig. 2). The simulation allows for haptic intervention, which is particularly useful during the initial exploration of the plate geometry and in case of failure.

4.2 Sealing Concrete Precast Joints

In the same 6-level parking structure, workers must seal 6000m of concrete joints between the prefabricated concrete slabs (Table 2). This multi-step process involves three different crews that perform: pouring concrete, shot blasting, and coating to water-proof the joint. During the first step, cement is poured using a pump with a hose. Shot blasting uses a Contec Modul 300 machine, and the waterproof coating is applied manually by a crew of 4 to 5 people.

Automating the concrete joint sealing task requires a robot similar to the Contec Modul machine carried manually today. The robot solution should autonomously control the flow rate of cement and other sealant materials, safely navigate the environment, keep track of progress,

Figure 5: Six-level prefabricated parking structure involving welding and joint sealing. Built by our partner Goldbeck.

Table 2: Sealing concrete precast joints performance

Concrete joints	Prod. (sec/m)	Total (h)	Prep./day (h)	Workers
Pouring	20-30	41.7	2	2
Shotblasting	10-15	20.8	1	1
3-layer coating	115	191.7	3	4-5

and identify the joints and corner points. In this paper, we use a pump and hose mechanism mounted on an omnidirectional base (Fig. 9) with a pressure sensor that allows the system to detect corners and control pouring height within the joint. The haptic interface allows an operator to reposition the robot and to feel the joint or obstacle in case of obstructions.

5 Experiments

This section summarizes the experiments for welding and sealing concrete joints. We propose an approach in which humans and robots can collaborate in challenging construction tasks. Both solutions deploy BIM at LOD 300 provided by the industry partner and the simulation and control environment SAI to incorporating haptic control in task space.

5.1 HRC Welding

The welding solution consists of a mobile platform equipped with a Panda Franka 7-DOF robot arm and welding end-effector, capable of moving autonomously along the concrete foundation until finding an anchor plate. The platform is tall enough to roll over the anchor plate once the welding is done and is also narrow enough to operate along the 60cm foundation width.

The robot is controlled in two modes: autonomous navigation in joint space signaled with a cyan sphere, and haptic control in operational space signaled with a green sphere (see Fig. 6).

In the autonomous navigation mode, the robot autonomously locates the plate position of the anchor plate from the BIM's approximate coordinates. Upon reaching the desired plate, the expert welder can take over the task using the haptic interface. This allows the welder to select the torch position and explore the plate geometry. Once the haptic welding is done, the operator can raise the end-effector to signal the robot to transition back to the autonomous navigation mode and move to the next welding plate.

To provide real-time force feedback to the welder, the simulation includes simplified collision meshes of the environment. The anchor plate is simplified to a rectangular mesh of the same size, while the welding tool utilized a cylindrical collision mesh (Fig. 7). This speeds up collision computation while providing sufficiently accurate force feedback.

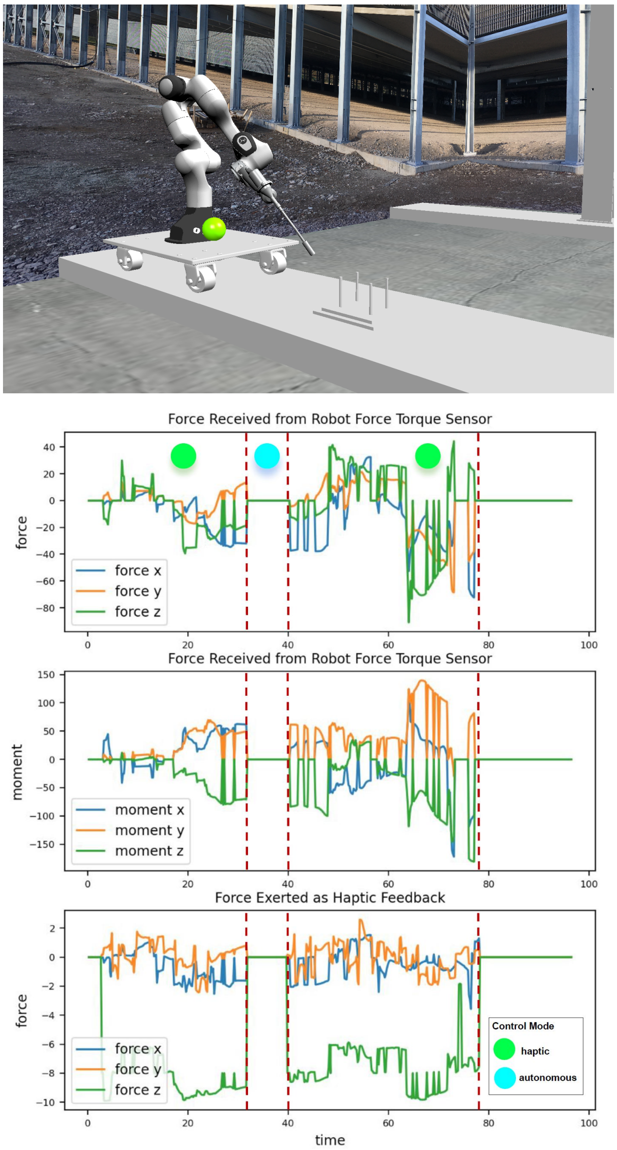

Figure 6: Haptic simulation and force feedback plot.

To determine contact between the welding gun and the concrete, we calculate the end-effector sensed force in the direction of motion. If $\boldsymbol{F}_{proj}$ is greater than threshold 0.5N, contact is "true", providing damped force and moment feedback to the user.

An added attraction force between the welding perimeter and the robot's end-effector helps the operator maintain the welding path. The real-time plot, including sensed forces and moments from the end-effector (Fig. 6), shows that with the addition of the attractive force, the user feels clamped to the surface so it is easier to follow the welding trajectory. The accumulated force exerted on the haptic feedback is the sum of the sensed force plus the attractive force.

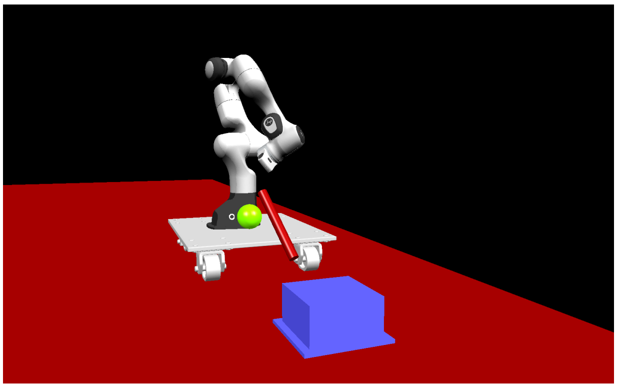

Figure 7: Collision meshes for contact resolution in simulation.

The attraction force applied to the user is given by

$$F_{attraction} = \frac{1}{2}\eta\left(\frac{1}{x_{current}} - \frac{1}{x_0}\right)^2 \tag{4}$$

where $x_{current}$ is the global position of the end-effector, x_0 is global the position of the edge of the polls.

The haptic feedback for the user is given by

$$F_{feedback} = F_{sensed} + F_{attraction} \tag{5}$$

where F_{sensor} is the force sensed by the robot's force torque sensor.

A position limit is added to the robot end-effector to prevent it from completing motions inside of the plate and to maintain safe contact during the welding operation.

Future work will learn a strategy to complete the weld based on the human demonstration of the task, extracting key parameters such as distance between the end-effector and the plate, as well as speed and orientation during welding execution.

5.2 HRC Sealing Concrete Precast Joints

The second experiment focused on the task of sealing concrete precast joints. The process involves joint identification, edge detection and tracking, and material pouring following a particular sequence to ensure structural soundness (Fig. 8).

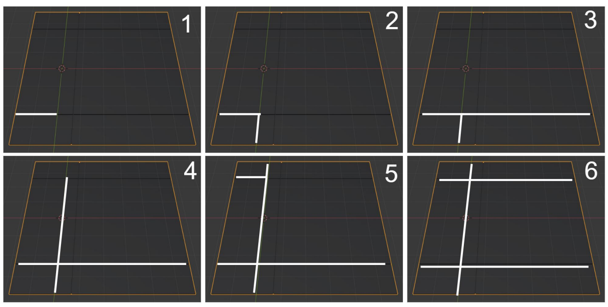

Figure 8: Concrete joints task schematics showing the concrete pouring sequence in six steps.

The concrete slab dimensions were obtained from the BIM. Additionally, the simulation includes collision meshes for each individual concrete slab and joint.

The autonomous controller uses the BIM coordinates to locate each joint. Upon reaching a joint, the nozzle is lowered, and pouring begins. During pouring, the height of the nozzle is controlled using a pressure sensor. When the joint is completely sealed, the nozzle is retracted, and pouring stops so that the holonomic base can move to the next joint.

An operational space haptic controller, that collects information about the sensed forces, allows an operator to assist the robot at critical points of the task such as corner points to confirm that the nozzle is aligned and the flap is rotated before continuing to the following joint.

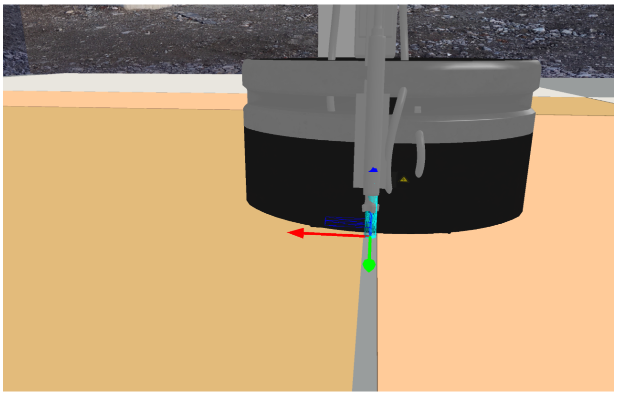

Figure 9: Close up of the joint sealing task in simulation.

6 Conclusions and Future Work

The experiments presented in this paper demonstrate synergistic collaboration between robots and human operators while performing two construction tasks - welding and joint sealing. The key elements that enabled this successful collaboration were: the use of a haptic device that facilitates operator intervention by allowing him/her to feel the environment, and a flexible control framework that allows for smooth transitions between autonomous robot skills and operator haptic control.

We expect this approach will provide the necessary support for tasks that are too complex for full automation. Additionally, data recorded during the operator's intervention can be used to teach the robot new skills and augment its autonomous capabilities. Overall, haptic interfaces provide an effective means for accomplishing challenging manipulation tasks in unstructured construction environments.

Future work will test these solutions on hardware using

7-DOF Franka Panda manipulators. The hardware prototypes will also allow us to collect operator feedback and gather task execution data such as accuracy and duration.

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