Generalised Framework for construction using Robotics

Abstract

The establishment of a generalised framework is done around robotic concepts that have been around for more than 30 years. Utilising advancements in technology as well as discoveries, optimisations and improvements made by research in construction robotics. This paper formalises the findings into a four-part framework that can be used as a starting point for interdisciplinary teams or to help breakdown the vast possibilities the usage of robotics can imply. This paper focused on using examples of robotic usages in the construction industry or finding robotic usage that was very close to construction in order to draw parallels.

Introduction

This paper proses a generalised framework for robotic construction from a robotics engineering perspective. The idea of automated construction has been analysed for the last 35 years (Paulson Jr., 1985). Whilst, as predicted by earlier research, the information technology available has drastically changed, it is possible to create this framework out of the original ideas proposed, developments in technology, and from current cutting-edge research. Current implementations of robotics in construction seemed to be used either for smaller one-off projects or large pre-fabrication assemblies. The aimed usage of this paper is to aid development of interdisciplinary projects in the area of construction robots to lay out a basic yet complete view into the fundamental aspects of robotics and its applications to construction. At the same time effort was put into making sure the framework itself is as solution neutral as possible so that it can be applied to as many automated or half automated robotic construction systems as possible.

Literature review

As an industry very reliable on manual labour, automation seems to be a perfect solution for all kinds of concerns as it could improve productivity and quality (Neelamkavil, 2009) whilst reducing manual labour and the possibility for accidents (Usmanov, et al., 2010). The current state of robotics is best described by Bock who says

> "Conventional construction gives birth to new technologies, which at the beginning phase (where we presently find ourselves) are inferior in performance due to technical, organizational, and economical obstacles as well as to limited integration within an economic environment still dominated by mature and conventional technology"
> (Bock, 2015)

Thus, when researching and designing construction robotics, it is essential to design around robotics, this is to help integrate the automation system with construction processes and structures by adapting both to each other as much as possible.

As the field of automated construction is a new field its implementations are not yet fully explored. Integrating it into existing or new structures by making a robot that mimics a human as closely as possible is one aspect a lot of research is concerned with, however robotics infrastructure does not dictate any physical attributes of the technology implemented (Ruggiero, et al., 2016). Thus, developments into physical end attributes can be unpredictable and innovations can surge at any given time. This demonstrates the need for a solution neutral framework as the framework itself cannot limit development by phrasing certain needs as having a specific solution. The fundamentals this framework is based on, i.e. how to specify, plan and execute the placement of building elements to achieve a final structure Liu, et al., (2019) and Everett & Slocum, (1994) are known and addressed by researchers in the area for decades, however it has not been put together into a formalised framework that can be applied to general automated construction. A framework that is solution neutral in its terms and helps break down the core elements of robotics may thus help interdisciplinary research teams to make sense of this unpredictable and yet undefined landscape.

Framework proposal

The overall outline of the framework proposed in this paper is constructed out of current ideas which are present in recent/modern research. Where appropriate these will be further broken down into their core aspects and discussed. If possible, the elements outlined will be explained with either actual cases present in current research or industry or this paper will propose a possible example if none can be found.

The framework is comprised of 4 parts:

- The Robotic platform
    - This outlines the overall physical attributes of the robot, discussing items like mobility and movement of individual components
- End effector and Structure design
    - Concerned with the design of elements that make up the structure and the fasteners used to connect them in relation to how the robot interacts with them in a meaningful way.
- Data acquisition
    - Discusses the need for sensor data, how sensor data can be stacked to improve overall performance and how to apply it to construction.
- Process monitoring
    - Outlines the usage of software to utilise sensor data for error correction.
    - Presents ways in which humans can have an insight into the current, planned and previous actions a system is doing.

The reason these four aspects are considered to be the fundamentals of any robotics framework is because they are the main aspects discussed in general robotics usage. They are also the aspects discussed when robots are applied to construction as far as the research of this paper and knowledge of robotics shows.

The advantages of the framework are that is does not mean the system deployed has to be a single fully autonomous robot. If full automation is not required and robots are there to assist humans rather than work independently then the weighting of each item can be changed. For instance a telerobotic system- a system that is still controlled by humans and has no processing power by itself- may still need data acquisition such as cameras or proximity sensors to aid the human who is controlling the robot but, it will need nearly no process monitoring.

If more than one robot is used this is not a problem because the framework does not dictate how may robots can or should be used and multi robot systems still utilise the 4 aspects of this framework.

One limitation with this framework is that although it was made to be as solution neutral as possible; future unpredictable development of robotics mean that extremely niche sectors or very experimental designs may only follow this framework somewhat.

Robotic Platform

There are many different types of robots in construction and assembly, some examples include 6 axis robots (figure 1) which rely only on multiple rotating joints and Cartesian (figure 2) robots which rely mainly only on linear joints.

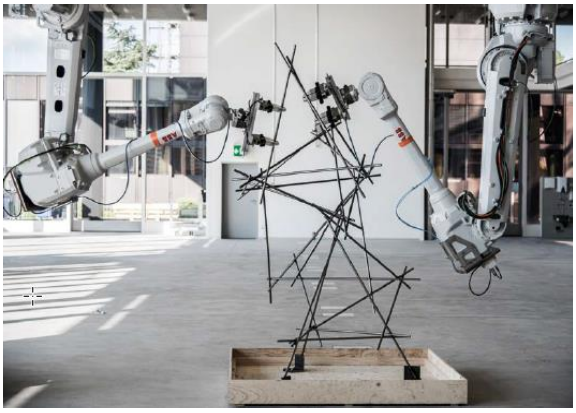


Figure 16 degree of freedom robots assembling a structure from steel (Parascho, et al., 2020, p. 27)

Figure 2 A Cartesian robot assembles prefabricated parts of a house. (Usmanov, et al., 2010, p. 6)

The most utilised are arm-based robots, these mimic the movement of a human arm in various degrees of freedom. A degree of freedom is defined as an axis the robot can move in- 1 rotational joint would result in 1 degree of freedom. 6 degrees of freedom is the minimum amount for freedom of movement of a rigid body in 3-dimensional space. These arm-based robots have more degrees of freedom that other types of robotic platforms allowing them to not only position an object in 3D space but also to orientate it, a crucial step for assembly. This also makes them incredibly versatile and one robot can do many different jobs. A disadvantage is that they are often limited in their workspace, usually to a hemi-spherical area which is defined in radius by the maximum extension of the robot (figure 3), this issue can be somewhat overcome by the addition locomotion which would expand this area.

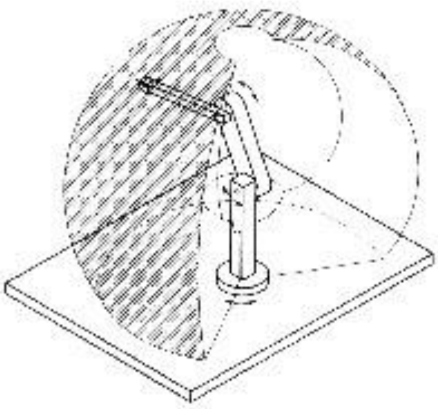


Figure 3. The maximum reachability of a robot shown by the sphere. (Society of Robots, 2014)

Cartesian robots are also used frequently for assembly processes that are based on layers. They are characterised by their inability to easily implement control of the orientation of the end effector and they must always be able to reach the destination of the object from above a seen in figure 4. The advantage of these robots is that they are much easier to program, are mechanically simpler and can generally hold larger payloads as they have full frame chassis as seen in figure 2 rather than just a single arm holding the total weight. Unlike typical Cartesian robots found in other industries such as 3D-printers, cartesian style robots used in the automated construction rarely use a full frame chassis and do not only rely on linear movement. This is because at this scale a full frame chassis is more expensive and is large therefore taking up a lot of space in transit and time to assemble. This undermines many of the advantages as it is impossible to have them run fully automatically. They do still have the advantage of being easer to program and being more mechanically simple. Figure 4 shows FBR's Hadrian x which uses a Cartesian coordinate system to build walls and structures. Other robots like this are used in Brick laying that take and stack bricks the same way a human would.

Figure 4. The Hadrian x uses linear mostly its linear actuators on a rotating platform to place bricks. (FBR construction, 2019)

Figure 5. The robot has 2 rotating joints for 2D movement and moves up and down on a pole. (San Fratello & Rael, 2020, p. 27)

Of course, there exists also hybrid approaches like SCARA robots (Selective Compliance Articulated Robot Arm). These are often cheaper than fully 6 axis industrial robots and due to them also relying on rotation they can more easily path curves which is not the case for Cartesian robots. These robots are in 3D-printing projects like Clay (San Fratello & Rael, 2020) (figure 5).

A way to approach this topic is to analyse and visualise what paths the robot takes but working backwards -starting at the destination, i.e. where the robot places an item and in what position and then working backwards to the point where the robot picks said item up. Thus, determining how articulations should be implemented for these paths to happen. This process is very dependent on the structure itself. The best way to categorise this is to analyse what tasks the robot must do. If, for example, it's assembly of panels with joints then the designed must consider:

- Picking up of panels or joints from the origin point
- Movement of panels or joint through space, preventing collisions with either the structure or the robot itself
- Placement of the panel in the position where it can be jointed with the other panels
- Placement or movement of the method that the panels are connected with, be that fasteners or some sort of substance.

This section only discusses robots that whose links are made from rigid materials. Soft robotics aims to use exclusively soft materials to achieve robotic arms that mimic the trunks of elephants or the tentacles of octopuses. This would mean that not only the links but also actuators, joints and sensor technology have to change from its current, rigid format to utilise soft materials. Additionally because, unlike rigid robots, there are no set joints around which movement takes place they are said to have hyper redundant degrees of freedom and are controlled very differently from conventional robots (Iida & Laschi, 2011). Thus, this section of the framework may not be able to be fully applied to this new field or robotics if it is utilised in construction in the future.

End effector and Structure design

The end effector plays a crucial role in the assembly of any assembly process as it is the tool that interacts with the structure. Therefore, it must be designed in conjunction with the structure's parts and joints. There are different ways to approach the design of the end effector. The adaption of end effectors to a specific task is already common in all robotic application and some designs may look like this:

Some may be custom made to suit this specific task

Figure 7. the end effector is made specifically to hold onto the shown bricks to place them without gaps (Vähä, et al., 2013, p. 9)

Figure 8. An end effector designed and refined to 3D print with a specific mixture of clay (Anton, et al., 2020, p. 291)

Some may be modified existing tools to work well with robotics

Figure 9. The use of comerically available chainsaws with triggers zip-tied in place. (Self & Vercruysse, 2020, p. 33)

The use of modified existing tools may be common practise to use as end effector in other industries where robotics is utilised however this paper could not find any use cases of this in the construction industry. What was found were tools that were designed for specific use. To help design a tool for a given application it can be evaluated by 2 different criteria: What is must do and what it should be.

What the end effector must do:

The end effector employed in any given robotic system must be uniquely designed for the task it completes. As said by Fratello & Real:

> "There is no use for a "generic" end effector. It must be designed to work only with the current assembly technique and said assembly technique must me universal enough for all applications. "
> (San Fratello & Rael, 2020)

The end effector must be designed to work well with all tasks it needs to complete. Often in construction this will mean a mix of gripping items and fasteners as well as using tools on the fasteners to tighten them. One approach is to make a specific but versatile end effector that can be very adaptive in the set of situations that could present themselves during the assembly of one specific structure. Such an end effector could be designed to grip and manipulate panels easily by resembling human hands. This would be a rather complex and difficult to program end effector, however, would be very versatile with the tasks it could perform. Another approach is to use a rather simple end effector and adapt panels and fasteners to it. Such a system has been co-designed to work with a singular hexagonal end effector using mechanical joints.

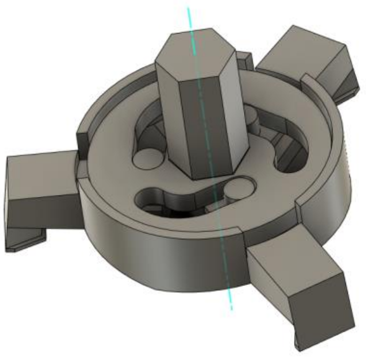


Figure 9. A joint whose arms contract as the hexagonal pin is turned. Locking in the panels.

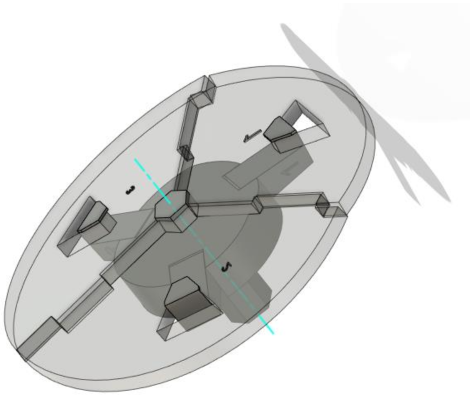


Figure 10. Another view of the joint. This time with cut outs of the panels.

If the system utilises multiple robots then often tasks are split between robots. Due to this each robot has less tasks to do, and its end effector can be designed to be more specific to the tasks it must perform.

What the end effector should be:

Certain design choices have impacts onto the behaviour or qualities of the end effector. A complex end effector that specifically does all the tasks required of it may be great for the assembly but a system that is too large and heavy impacts both the maximum payload that can be moved by adding the weight onto the system. It also decreases the spaces the end effector can go in as it may be too physically large (Hargreaves, n.d.). Reachability must be assured. This is partly addressed with a small end effector. This is an aspect that gains new importance with robotics as it often assured for manual assembly. The differences in operation between humans and robots is that the new-often more varied than human- mechanical layout of the robot must be considered (Bonwetch, 2012).

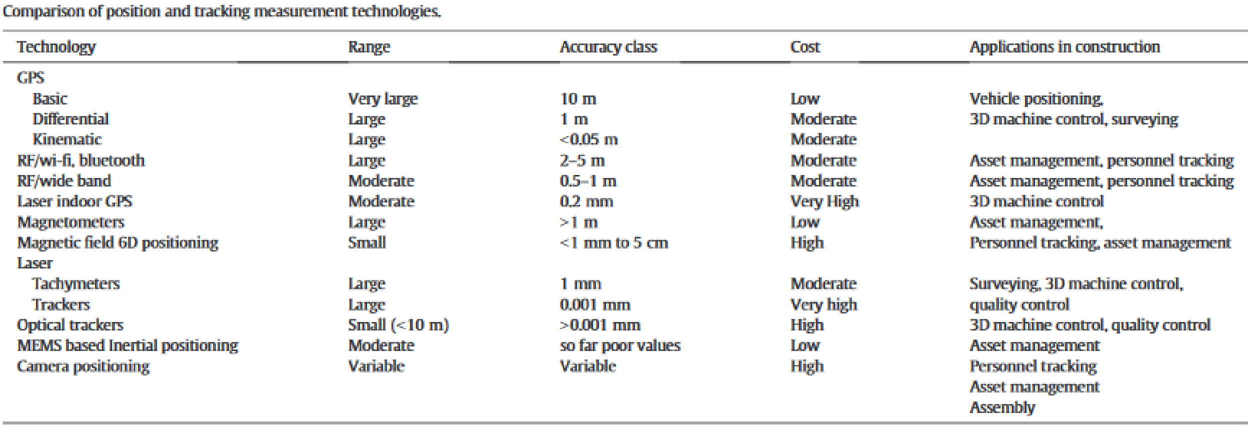
Data acquisition

The collection of information regarding the construction project is essential throughout its entire course. This includes support planning, procurement, control and the construction of the structure itself (Vähä, et al., 2013). Whilst all of these tasks differ in what is needed from the robot, the data acquisition remains the same and it must be noted that some tasks may not be needed for all structures. All the different tasks that require data acquisition will therefore be condensed into just the construction of the structure.

Error can occur due to a variety of factors such as temperature fluctuations or manufacturing tolerances. For correct operation and the correction of errors it is crucial for a robotic assembly system to be aware of its surrounding and act to correct errors and deviances from the norm. This monitoring also allows comparisons between several assemblies and thus to act as quality control.

This means that any robotic component within the system needs both data acquisition, in forms of sensors, and error correction, in form of computer or micro-processor. This can be done through many ways as there are a plethora of sensor platforms that utilise a vast array of wave lengths from the electromagnetic spectrum.

An overview of a few sensors used in modern robotics systems is provided in figure 11 below. Although there are many more sensor types to choose from this shows how sensor platforms can differ from one another and what application usage they have outside of construction robotics.



Comparison of position and tracking measurement technologies.

Technology	Range	Accuracy class	Cost	Applications in construction
GPS				
Basic	Very large	10 m	Low	Vehicle positioning,
Differential	Large	1 m	Moderate	3D machine control, surveying
Kinematic	Large	<0.05 m	Moderate	
RF/wi-fi, bluetooth	Large	2–5 m	Moderate	Asset management, personnel tracking
RF/wide band	Moderate	0.5–1 m	Moderate	Asset management, personnel tracking
Laser indoor GPS	Moderate	0.2 mm	Very High	3D machine control
Magnetometers	Large	>1 m	Low	Asset management,
Magnetic field 6D positioning	Small	<1 mm to 5 cm	High	Personnel tracking, asset management
Laser				
Tachymeters	Large	1 mm	Moderate	Surveying, 3D machine control,
Trackers	Large	0.001 mm	Very high	quality control
Optical trackers	Small (<10 m)	>0.001 mm	High	3D machine control, quality control
MEMS based Inertial positioning	Moderate	so far poor values	Low	Asset management
Camera positioning	Variable	Variable	High	Personnel tracking Asset management Assembly

Figure 11. Sensors. (Vähä, et al., 2013, p. 4)

Figure 13. SICK sensor mounted directly next to the end effector. (Mead, 2019)

Deploying just one sensor close to the end effector may suffice for some assembly tasks, but often multiple sensor systems, which can form a hierarchy of perception, can be utilised to have additional benefits (Dogar, et al., 2015). This creates robustness through redundancy. Multiple diversified sensor systems can reduce error detected through just one system. The time to execute can also be reduced as the computer can make faster more definitive actions because the additional data, through its elimination of errors, allows a greater insight into choices a computer may take (Dogar, et al., 2015). Both benefits also mean an improved precision and repeatability.

The paper that studied this hierarchy of perception (Dogar, et al., 2015) analysed a potential problem that this approach could have. When the number of robots deployed in the system increases, having each robot have its own sensor system would create too much data and thus either slow the system down or increase cost and weight to accompany larger processing units. In this case a sensor system that maps not from the perspective of the robot, but the entire workspace would be employed. This would be directly linked to each robot (Dogar, et al., 2015) and would allow prevent this issue. This system can be implemented with the inclusion of stationary sensors mounted across the workspace, or with additional robots whose whole purpose is to move, map and analyse workspaces. This method is especially useful in workspaces that can change or are difficult to map from a single angle or small number of set angles.

For robots that are not stationary one must also consider the accuracy of the locomotion employed. No system is perfect and additional data acquisition may be needed to ensure errors don't accumulate over several movement paths. On way of reliably doing this in indoor spaces was presented in the following paper where the distance to walls was used. Accuracy achievable by automatic mapping of indoor construction environments. It was found that when robot positioning was precise (orientation and location errors of 0.2° and 3 cm, respectively), the achievable accuracy of indoor environment mapping was 3–5 cm (Elattar, 2008). For construction tasks liks spraying foam on the scale of an entire room this would suffice however, if more accuracy is needed, this would allow them to position the robot close enough to a destination that other sensor platforms could guide it more closely to a destination if need be. Another paper also employed self-powered locomotion-based platforms (Yablonina , et al., 2017). Utilising a camera system, the robots worked well with a software system giving them 10-20mm precision with a camera. The accuracy here was crucial as filament strings were routed along attachments in a wall to create a structure to hold a person. Reportedly it went well citing no failures to attach the filament and being able to achieve the goal of holding a person.

Process monitoring.

Process monitoring has 2 significant aspects: Human process monitoring and internal computing process monitoring. These are discussed separately below.

Human Process monitoring

Figure 13. The use of a PDA to show the result for referencing (Balaguer, 2004, p. 5)

Figure 14. The use of AR to show the result for referencing (Alder & Suerth Jennifer, 2019)

Human process monitoring means that humans are given a varying amount of insight into the calculations, sensor data and actions a robot could or will take. This allows for optimisations and gives people insights into the next steps the robot will take as well as additional info such as time elapsed and an estimated time remaining. One end of the approach would be the usage of mobile end devices as it's very easy for anyone to have an insight into the working of the robot. Whilst there may be an issue with the processing power of such devices not allowing for much interaction, the info displayed could be a final 3d image of the structure giving workers an idea of how big the end structure would be and working around it to ensure the robot has enough space to complete the task. At the other end of the spectrum one could use VR or AR, allowing for a fully immersive experience. When connected to a workstation this would allow for enough processing power to have a digital 1 to 1 copy which could also show sensor data and the differences between the programmed and error corrected path (Balaguer, 2004) (Neelamkavil, 2009).

Internal computing process monitoring

Internal computing process monitoring is taking the data acquisition and utilising it to make the decisions to correct errors and plan the next step. This is needed to account for errors even in systems that have pre-programmed paths.

Often only vague directions are given to the control system and an algorithm or artificial intelligence plans and executes tasks. At its simplest an adaptive system needs a loop function. This is a concept that explains how the computer utilises data.

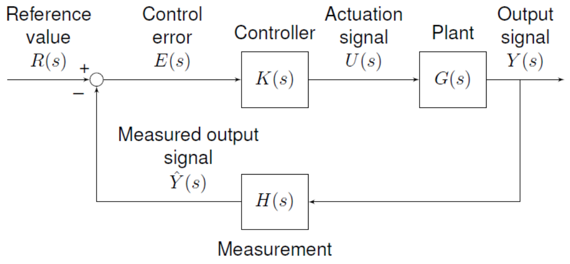


Figure 15. A closed loop set up. (Zoran, 2020)

The concept of closed loop systems can be explained using a compass. True north is the end position of the compass whilst the magnetometer sensor reading is the actual position. At any given time, the difference between true north and the reading of the sensor is taken and is the error. This error will usually go through some sort of algebraic function to make larger errors more significant or smaller errors less significant. This error is then used to control some sort of mechanism, in the example of a compass this could be a motor the sensor is connected to. The error value is used to generate a signal to the motor proportional to the size of the error value. This is a very common, simple and versatile way of utilising sensor data. The key function is to correct errors in planned action. It cannot determine what action to take given a set number of inputs- it can only take in errors and compare these to a nominal value. This can be used for repeated building of identical structures where Engineers have spent time calculating and optimising the path the robot takes and what actions it does and in what order. Outside of construction robots the use of closed loop feedback system has been utilised in a complex gripping mechanism that utilised closed loops to make complex evaluations of the objects it held in order to have a sufficient grip without crushing the object (Yuen, et al., 2018).

At its most complex, would be the usage of AI to not only correct errors but also make decisions that directly affect the order of the construction process. Here a program is trained in one of 3 ways. Supervised learning is where the AI is given a set of examples with correct responses, the AI must then generalise to respond correctly to all different inputs. Unsupervised learning is where no solution is given but problems must be grouped to be categorised. Lastly, reinforcement learning is where both techniques are used together (Marsland, 2015). This approach is much more robust as the closed loop feedback system can deal with more complex errors and may not even need any pre-programmed actions potentially just requiring a set of rules to follow. Here the robot can take more complex actions without the need for human intervention. This is an excellent approach for a robotic system then builds structures that vary in the way they are assembled as it means the responsible engineers don’t have to program tool paths for every available structure. However, training the AI takes data, something that isn’t always available, and it needs to be tested extensively before it can work on its own without any supervision. This takes a lot of time and effort and this corresponds to large costs. AI is already used in situations that change every time something is assembled, for example cranes (Kang & Miranda, 2006) where the AI managed to implement path-planning, collision detection and optimisation for a safer and more efficient assembly of cranes. In the research the new proposed method that involved the usage of ai which showed that previous models underestimated assembly time as the AI had learned more sophisticated collision avoidance which previously had been overlooked.

Conclusion

This paper presented a generalised Framework for construction using Robotics. As an area that is just emerging with great potential to change an industry the generation of a solution neutral framework made by this paper should act as a starting point for interdisciplinary teams that are working on integrating robotics with construction. None of the concepts described are new and this paper has demonstrated that all the points made are already in use in construction robotics to some extent or are relevant enough in adjacent industries to be considered for construction. From the way the framework is presented and laid out, it can be used on any robotic system either to design it to work on a project or to inspect existing systems for adaptation or evaluation. The hope for this framework is that it can help with the basic aspects of robotics and that it can be adapted in the future with improvements in AI, hardware and miniaturisation of technology that all allow for more complex systems and thus better assembly robots. Even if the industry rapidly changes to incorporate new technologies not discussed in this paper the four discussed points will still be of relevancy just their execution will differ.

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