Development of Remote Controls for the Motorized Polarization Controller in LIGO's Arm Length Stabilization System

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Abstract

LIGO's arm length stabilization (ALS) system allows the arms of the interferometer to be locked separately, decoupling these two degrees of freedom from the Fabry-Perot and recycling cavities; this system faces issues with polarization drift along fiber optic cables, however, due to factors such as thermal stress, mechanical stress, and irregularities in the shape of the core. If this drift is not corrected, the mismatch in polarization can prevent the interferometer from observing. Currently, this drift is corrected by a motorized polarization controller (MPC) that must be adjusted manually on a regular basis. This project aims to develop comprehensive, user-friendly, and robust remote controls for the polarization controller to streamline the drift correction. The controller was connected through a serial port to TwinCAT Programmable Logic Controller software, on which the controls were written in IEC-1131 structured text. User input through a graphic interface is interpreted and written to this code, allowing the user to remotely control the polarization. In the future, this program could be used to automate the correction process.

1 Introduction

The gravitational wave detectors at LIGO Hanford Observatory (LHO) and LIGO Livingston Observatory (LLO) are specialized Michelson interferometers with 4 km long arms that convert space-time perturbations predicted by Einstein's theory of general relativity into a measurable signal [1]. By measuring to a high precision the distance traveled by two beams of light, the interferometers are able to detect differences in this distance produced by the stretching and squeezing of space-time by gravitational waves. The difficulty in this measurement is due to the length scale of these perturbations; this requires both that the interferometer mirrors are isolated from disturbances and that the noise encountered is quantifiable and removable. Thus, arm length stabilization (ALS) is essential. The current ALS system, however, faces issues with the drift of the polarization of light along fiber optic cables. This drift is corrected by a motorized polarization controller (MPC) that is adjusted manually on a regular basis. As aLIGO progresses, it is important to maximize the time spent locked and observing; by streamlining and digitizing the process to correct this polarization drift, we will allow for greater efficiency. The goal of this project was to develop remote controls such that an operator familiar with the physical device will intuitively be able to perform the same functions remotely using a user interface. This code would allow for more than just remote controls, however; it would also allow for data acquisition (DAQ) storage of the numeric channels for analysis, easier monitoring of the MPC settings, hourly snapshots of the state of the system, and control and data system scripting with the potential to automate the control of the MPC [2].

1.1 Arm Length Stabilization (ALS) System

In order for the interferometer to be functional, the Fabry-Perot cavities, the power recycling cavity, and the signal recycling cavity must be kept locked on resonance. For aLIGO, a stabilization system was devised to make locking reliable and repeatable using active feedback control. The arm length stabilization (ALS) system locks each arm cavity individually and separately from the central recycling cavities using lasers mounted behind each end test mass; they are doubled Nd:YAG lasers operating at 532 nm (green) deployed at each end station to distinguish them from the main laser. [3] By locking the arms separately, the ALS decouples these degrees of freedom.

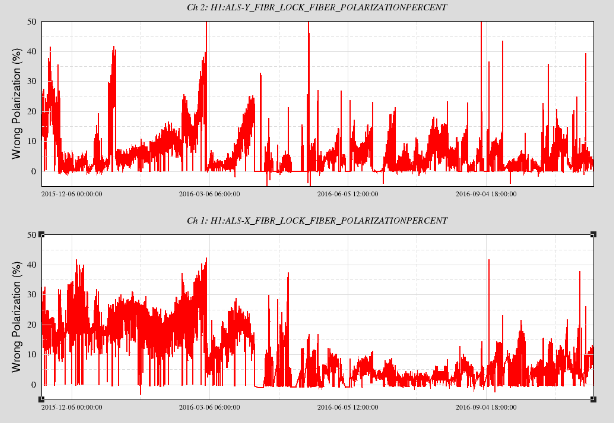


Figure 1: Percent of light rejected in ALS due to mismatch in polarization, observed over the course of a year. Ideally, this value is less than 5%; if this value gets too high, it must be corrected or observation is not possible. The sudden drops in polarization are due to active correction from the MPC by an operator. [4]

To reduce the initial frequency error and resolve discrepancies between the ALS lasers and the main laser, the end station laser is phase-locked to the main laser frequency. To do that, a sample of the main laser beam is sent over a fiber optic cable to the end station to act as a phase reference. The fiber absorption at 532 nm is large, so 1064 nm light is used [3]. Once the auxiliary laser is locked to the fiber transmission, the output of the laser is locked to the arm cavity. Unfortunately, the drift of polarization of the light over these fiber optic cables causes some of that input light to be rejected due to a mismatch of polarization. Figure 1 shows the trend of this drift over the course of a year by tracing the percent of light rejected due to polarization mismatch. This drift is inherent, and can be caused by factors such as thermal stress, mechanical stress, and irregularities in the shape of the fiber core. [5] To correct this drift, a polarization controller was installed to manually adjust the polarization across the fiber optic cables; this polarization controller is part of a larger fiber noise cancellation scheme, located in the corner station. [6]

1.2 Motorized Polarization Controller (MPC)

The motorized polarization controller used at LHO in the ALS system is a dual channel MPC1-02 from FiberControl. It alters the state-of-polarization of single mode optical fibers using stress-induced birefringence while minimally

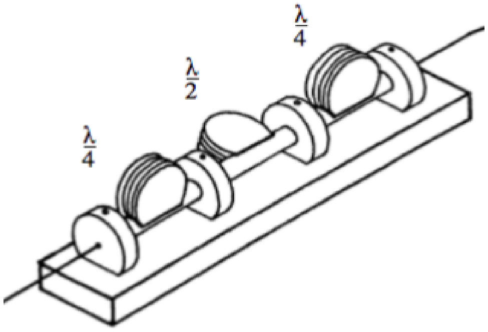


Figure 2: Fiber polarization controller consisting of three sequential Lefèvre loops. The orientation of these loops determines the state-of-polarization. [8]

impacting the insertion loss, reflection, and PDL [7]. A continuous length of fiber is formed into three Lefèvre loops, each mechanically connected to a paddle for independent motion [7]. These loops act as three effective fractional waveplates (or retarders); with these three degrees of freedom, they can transform any arbitrary waveform into any other, providing complete coverage of the entire Poincaré sphere. The first Lefèvre loop acts as a quarter waveplate ($\frac{\lambda}{4}$) to transform elliptically polarized light into linearly polarized light. The second acts as a half waveplate ($\frac{\lambda}{2}$) to rotate the linear polarization. The final acts as a quarter waveplate ($\frac{\lambda}{4}$) to transform back to elliptically polarized light, if required [5]. These three Lefèvre loops are labeled in Figure 2. As the paddles are physically rotated, the stress produced by this rotation changes the internal birefringence of the fibers, altering the polarization of the light. Because the MPC is designed to operate over two channels, two independent fiber strands formed into loops exist inside the box.

1.3 Effects of Twist and Bend on Fiber Optics with Stress Induced Birefringence

A medium with birefringent properties has different indices of refraction between two orthogonal eigen axes; when light propagates through that medium, its state of polarization is changed [5]. The Lefèvre loops within the MPC use the birefringence of the optical fibers in two ways. First, the fiber is made to act as a fractional waveplate through the bending of the fiber around each paddle. Second, the state of polarization is rotated through the twisting of the fiber as those paddles are rotated.

By bending the fiber around a set radius, the birefringence of the fiber changes such that it acts as an effective waveplate. This effect can be described by

$$\phi = \frac{2\pi^2 aNd^2}{\lambda D} \tag{1}$$

where ϕ is the retardance in radians, a is a constant dependent on the material of the fiber, N is the number of loops, d is the fiber diameter, λ is the wavelength of the light along the fiber, and D is the diameter of the loop [8]. By setting the retardance to either $\frac{\pi}{2}$ (corresponding to a change of $\frac{\lambda}{4}$) or π (corresponding to a change of $\frac{\lambda}{2}$), the necessary size of the loops and the number of turns can be determined, with the limitation that the diameter must not be smaller than the fibers can physically bend without injury. Once the first loop has been set as an effective quarter waveplate, we can approximate that it produces a phase shift of $\frac{\pi}{2}$. If the incident light is linearly polarized, with a wave equation of

$$(E_f\hat{\mathbf{f}} + E_s\hat{\mathbf{s}})e^{i(kx-\omega t)}$$

the final light will be shifted by $e^{i\frac{\pi}{2}}$, producing elliptically polarized light with a wave equation of

$$(E_f\hat{\mathbf{f}} + iE_s\hat{\mathbf{s}})e^{i(kx-\omega t)}$$

Similar calculations can be done to describe the transformation from elliptical to linear polarization, as well as the effects of the effective half waveplate. [9] Because the MPC is designed to act over a range of wavelengths, however, the paddles act only as effective waveplates with limited precision, and the polarization change is not exact [7].

Once the paddles have been set at a certain diameter and number of coils, they can be rotated to rotate the angle of the polarization. Because this twist exists in the medium twist regime where $\tau \approx \beta$ (that is, where the twist rate is of the order of the linear birefringence), the effect of a twisted rotation on the polarization can be described by

$$\alpha = g\tau \tag{2}$$

where α is the change in polarization angle, g is a constant determined by the elasto-optical coefficient of the material and the refractive index of the core, and τ is the physical rotation of the paddle. The constant g is further described by

$$g = -n_0^2 p_{44} \tag{3}$$

where the elasto-optical coefficient is given by

$$p_{44} = \frac{1}{2}(p_{11} - p_{12})$$

and n_0 is the index of refraction for the fiber. [10]

This can be derived by considering the influence of a shear strain S on a single-mode fiber using dielectric perturbation theory. If we consider the strain as causing a small dielectric perturbation, we can write that perturbations as

$$\Delta\epsilon = \epsilon_0 n^4 \begin{bmatrix} 0 & p_{44}S \\ p_{44}S & 0 \end{bmatrix} \tag{4}$$

By using perturbation theory, we can solve for the eigenvalues of the following problem

$$\begin{bmatrix} \beta^2 + 2\beta_0\kappa_{11} & 2\beta_0\kappa_{12} \\ 2\beta_0\kappa_{21} & \beta^2 + 2\beta_0\kappa_{22} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \beta^2 \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \tag{5}$$

where β_0 is the propagation of the single mode before the perturbation of the strain, and the coupling coefficients are defined as

$$\kappa_{nm} = \frac{\omega}{4} \iint \varepsilon_n^* \Delta\epsilon \varepsilon_m \, dx \, dy \tag{6}$$

The eigenvalues of the problem above are given by

$$\beta^2 = \beta_0^2 \pm 2\beta_0\kappa_{12} = \beta_0^2 \pm \omega^2 \mu\epsilon_0 n^4 p_{44} S \tag{7}$$

The change in the refractive index, or stress induced birefringence, can then be written as

$$\Delta n = n^3 p_{44} S \tag{8}$$

which leads to Equation 3. [9]

Despite the relatively simplicity of these equations, it is difficult to apply them to the reality of the MPC. First, because the three paddles are all adjusted, there are multiple points of twist in multiple directions. The inherent drift of the polarization due to external factors, as well as the internal imperfections of the fiber, also make it difficult to reliably predict the resulting polarization for a given paddle configuration. The biggest issue faced in that prediction, however, is due to the fact that the coils of fiber in each paddle act only as effective waveplates. Because they are designed to operate at a range of frequencies, they do not behave as ideal waveplates. The results of an investigation into this behavior can be seen in Figure 3. By using a polarimeter to visualize the change of polarization for a given paddle rotation, Thorlabs was able to characterize the behavior of their model of a loop-based motorized polarization controller across two different wavelengths. At neither 1310 nm nor 1550 nm did the quarter waveplate act as the ideal would, as shown in blue. These measurements were taken as one of the quarter waveplate paddles was fully rotated, with the other two paddles held at 0 degrees. While there is some directionality to the path traced on the Poincaré sphere, as the paddle created displacement largely in vertical direction between the circular polarization poles, the change in polarization is not as simple as the ideal retarder. Because of this inherent uncertainty, it it not viable to attempt to calculate the necessary paddle orientation for a given polarization adjustment. Further, even if that position was reliably found, it would continue to drift over time due to temperature fluctuations, as that is not controlled along the arms of the interferometer.

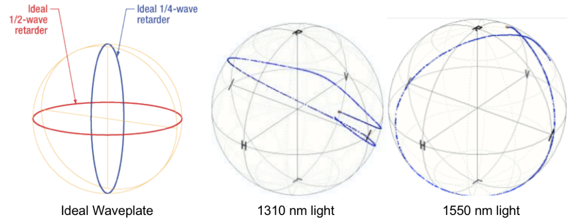
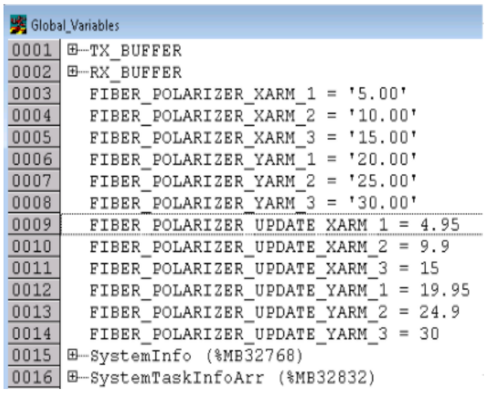


Figure 3: Visualization of ideal quarter and half waveplate shown on the Poincaré sphere, as compared to the results of the behavior of a given quarter wavelength paddle in a polarization controller for two wavelengths within design operation. [11]

2 Methods

Because the interferometer is largely controlled remotely through the control room computer system, there exists a platform at LHO that depends on a set chain of command between the user and the hardware for "slow controls" that are altered at a lower rate. LHO graphical user interfaces are built and run through motif editor and display manager (MEDM). When a user issues a request through an MEDM screen, it is written to the experimental physics and industrial controls system (EPICS) database. An input output controller (IOC) then writes this new value to code written on TwinCAT 2 Programmable Logic Controller (PLC) software in IEC-1131 structure text. This PLC code then communicates with the hardware, in this case the MPC, through a serial connection to EtherCAT bus terminals, which is used to run slow controls [12]

For these digital controls more than a simple command-and-response communication is required. Because the TwinCAT software continuously loops through the code, there must a robust state machine that is able to only move past start when a request is given, and return to start after that request has been executed. The MPC also has limited angular resolution; thus, the state machine must also inquire into the final angular position of the adjusted paddle, and update the user with this information. The state machine begins with the case statement in a start position; if there is a request to process, it then moves on to the interpret position to parse the syntax of the request. Then, it moves to the communicate position, where the request is sent to the MPC and its response is recorded. Next, the update position inquires as to the success of the request and the final position of the paddles. Finally, the update position passes this information to the user and sets the request as complete and the MPC as not busy.



```
⊞TX_BUFFER
⊞RX_BUFFER
  FIBER_POLARIZER_XARM_1 = '5.00'
  FIBER_POLARIZER_XARM_2 = '10.00'
  FIBER_POLARIZER_XARM_3 = '15.00'
  FIBER_POLARIZER_YARM_1 = '20.00'
  FIBER_POLARIZER_YARM_2 = '25.00'
  FIBER_POLARIZER_YARM_3 = '30.00'
  FIBER_POLARIZER_UPDATE_XARM_1 = 4.95
  FIBER_POLARIZER_UPDATE_XARM_2 = 9.9
  FIBER_POLARIZER_UPDATE_XARM_3 = 15
  FIBER_POLARIZER_UPDATE_YARM_1 = 19.95
  FIBER_POLARIZER_UPDATE_YARM_2 = 24.9
  FIBER_POLARIZER_UPDATE_YARM_3 = 30
⊞SystemInfo (%MB32768)
⊞SystemTaskInfoArr (%MB32832)
```

Figure 4: Command and response as shown in TwinCAT variables. These values are be shown in a user interface for the finished controls; here, they are manipulated through the software for testing. The limited angular resolution of the MPC requires that the user be updated on the final angular position after each command is given.

3 Results

3.1 TwinCAT PLC

Once the MPC was connected to the PLC software, the next goal was to establish communication and response. While the communication was easily established, the MPC did not initially respond as expected to simple requests. Instead, it echoed back any request that it was sent. After much trial and error, the proper syntax was discovered such that the MPC would implement any change requested. After that was established, the state machine was tested for these simple direct requests, such as the direct degree requests, and was proven successful, as shown in Figure 4. Note that the final values reflect the limited angular resolution of the MPC. When a position is requested that is not a multiple of 0.15, the MPC will move the paddle to the closest angular position without exceeding the requested angle. It is also important to recognize that the MPC does not consider the absolute value of the requested angle; instead, it considers less negative numbers to be larger. Because of this, when position is requested to be 50 degrees, the final position is 49.95, but when the position is requested to be -50 degrees, the final position is -50.10.

To mirror the functionality of the physical MPC more complex commands are also required. First, it was essential to have the ability to scroll through angles, as the process for correction involves scanning each channel for the position with the lowest rejection. Since these positions are not known, it does not make sense to have remote controls centered only on direct angle input. Instead, the multifunction knob on the unit (which allows the user to press to change step size, click right to step angle in positive direction, or click left to step angle in negative direction) was replaced with positive and negative scroll buttons and a direct input for the size of each step. This scrolling functionality was established by setting an angle step size and determining if this step size need to be added or subtracted from the current angular position. Second, it was necessary that the user be able to input the step size to allow for both coarse and fine adjustment. When the polarization is corrected, the random walk through the paddles begins with large steps and refines down as a minimum is approached. Because of the limited angular resolution of the paddle position, it is best if the entered step size is a multiple of 0.15 degrees. However, any step size can be used; the result is that the final paddle position will not be exactly the amount requested. The position display reflects this without error.

Other functions added to mirror the physical MPC include a center command, a command to reset the MPC, and the ability to control the speed of the paddle rotation for each channel. The center command sets the paddles of a given channel at 0 degrees, and allows for both quick adjustments and a way to recalibrate the waveplate positions should the user suspect a calibration error. The reset command also allows the user to recalibrate the MPC by returning the machine to factory settings. Because of the extreme nature of the cold reset function, as it wipes the memory of the MPC, this function was not included on the user interface. The ability to control the speed of the paddles was similarly included in the base code but not the user interface as it is so rarely used.

There also are additional functions required due to the nature of the remote controls that were not required for physical controls. For example, it was important that the remote user be able to rescan the current positions of each paddle so that the remote display is accurate, for two reasons. First, there is the possibility that the physical MPC could be changed without the knowledge of the remote user; because the MPC does not send out a serial communication update when that happens, the remote user would not be aware unless the position was rescanned. This is unlikely to happen, however, as remote commands always supersede local commands, and lock out the local user when issued. Second, and more important, when the MPC is powered off after use to avoid noise contamination, the paddle positions set remotely are not stored in permanent memory. Thus, when the MPC is powered back on, it reverts to the last physically set positions and the variables stored remotely are no longer accurate; the remote user must request an update to see the accurate positions. While this loss of information is inconvenient, it is not critical to the functionality of the polarization controller, as the only time the MPC is powered on is when the polarization must be adjusted. Further, those variables are also stored in the code records, making those positions relatively simple to return to, if the user desires.

Another additional function required for remote controls is the ability to monitor the status of the MPC and inform the user when it is busy processing a command. This busy monitor is set TRUE when a command is sent, and FALSE once the MPC reports its final position. If the command is processed incorrectly, the busy monitor remains TRUE until the error is resolved and a command is fully processed.

It also essential to have robust errors and error interpretation. If an error is encountered, the state machine is returned to start, and the user is notified through a red box on the user interface around the break point. There are also associated error identifications to inform the user if the error is due to serial communication (error in sending or receiving), user input, or unexpected syntax from the MPC. These errors remain flagged until the command is resent and processed correctly; by returning the code to the initial case statement when an error is encountered, error recovery is possible without any code reset.

3.2 MEDM User Interface

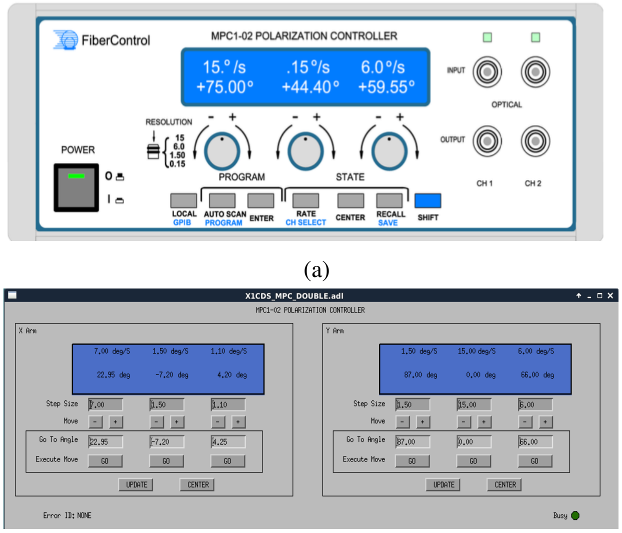
After addressing these details of the code, an interface for the controls was created using MEDM (motif editor and design manager), which writes variables through the EPICS OPC server to the TwinCAT code. These variables can either be written by the user using direct input for real number input and button controls for boolean input, or simply monitored by the screen. Each button or value is tied to a variable on the TwinCAT code; when that variable is in error, a red error box appears around it to notify the user. When a command is processed, the busy monitor flashes green to simulate a green LED.

The final MEDM created is shown in Figure 5, with a representation of the physical face of the MPC for comparison. To make this interface as generic as possible, a template interface for controlling a single channel was made first using macro substitution, which allows the interface to be transferable to different systems between LHO and LLO. Once this was complete, the final MEDM was made by putting together two channel controls for the X and Y arms.

4 Conclusions and Future Work

The code written on TwinCAT PLC software and controlled through an MEDM user interface has been proven functional and robust. Through running a continuously looping state machine, the code is able to interpret and send user requests, record the response of the MPC, and update the user as to the success of her request. It is also able to handle errors and return to start without losing information. The MEDM user interface created is intuitively simple to use, because of its similarity to both the physical appearance and the functionality of the MPC. These remote controls allow not only for more efficient and convenient adjustment of the polarization along the fiber optic cables in LHO's ALS, but also for the storage of the numeric channels associated with it. The storage of these variables makes it possible to examine the trend of the settings used on the MPC. Over time, it is possible that a pattern could emerge, and the root cause of the drift could be better understood.

There remains future work for the expansion of the code. First, because of the noise generated by continu-



(a)

X1CDS_MPC_DOUBLE.adl

MPC1-02 POLARIZATION CONTROLLER

X Arm

7.00 deg/S 1.50 deg/S 1.10 deg/S
22.95 deg -7.20 deg 4.20 deg

Step Size 7.00 1.50 1.10
Move - + - + - +
Go To Angle 22.95 -7.20 4.25
Execute Move GO GO GO
UPDATE CENTER

Y Arm

1.50 deg/S 15.00 deg/S 6.00 deg/S
87.00 deg 0.00 deg 66.00 deg

Step Size 1.50 15.00 6.00
Move - + - + - +
Go To Angle 87.00 0.00 66.00
Execute Move GO GO GO
UPDATE CENTER

Error ID: NONE
Busy ●

(b)

Figure 5: (a) Graphic of the face of the MPC1-02. The two channels are controlled through the same face by switching channels manually. [7] (b) User interface created using MEDM. Each face represents the controls for a given channel.

ously running the MPC, it is important that the remote controls include a power on/off switch, which will require external hardware as this command is not internal to the MPC. Another opportunity for the expansion of this program is the automation of finding the ideal settings for the MPC1. Currently, to achieve a polarization that results in less than 5% of the light rejected, the knobs of the MPC1 are adjusted at random until the percent of rejection is minimized. Now that basic computer controls have been established, it will be relatively simple to program a way to cycle through each knob until the minimum is reached, without manual adjustment.

There is also potential for investigation into the subtitles of the functionality of the MPC. First, a discrepancy between the set speed of the paddle motion and the apparent speed of motion as reported by the busy monitor in the code should be investigated. Even when the rotation speed of the MPC's paddle is set at its lowest setting of 11.3 degrees/second, it appears to complete a motion of 100 degrees in a fraction of a second. This could be resolved by opening the MPC and observing the actual motion of the paddles, but that was not attempted during this project due to the potential harm it could do to the machine. Another investigation into the function of the MPC is to measure the exact retardance of each effective waveplate at the given wavelength of light used at LHO. While it is know that the paddles do not act as exact waveplate, if the effective behavior were known it would make it more feasible to predict the necessary configuration of the paddles, and potentially allow for a direct correction of the polarization rather than the inefficient random search that is currently used.

5 Acknowledgments

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