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INTELLIGENT MACHINE GUARD MONITORING

A wireless system to improve miner safety

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RESEARCHERS AT THE National Institute for Occupational Safety and Health (NIOSH) are developing an intelligent machine guard monitoring and proximity detection system designed to mitigate machine entanglement and maintenance-related injuries and fatalities prevalent in the mining industry. This experiment was designed to develop a monitoring system consisting of mechanical/magnetic switches and sensor beacons capable of wirelessly transmitting information about a belt conveyor's machine guards to a remote computer. The data transfer was carried out via an off-the-shelf wireless communication system and displayed on a Web-based user interface. Successful operational tests demonstrated the functionality and effectiveness of the system in monitoring guard placement status

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and remotely identifying the location of any removed guards using each sensor's unique identification number. The integration of wireless safety technologies such as this system is expected to improve the safety of miners by providing additional protections against machine guarding-related injuries.

NIOSH RESEARCHERS ARE INVESTIGATING AN INTELLIGENT METHOD OF ADDRESSING MACHINE GUARDING ISSUES.

Improving Miner Safety

An analysis of the Mine Safety and Health Administration (MSHA) accident and injury database for coal and metal/nonmetal mines showed that, from 2001 to 2010, nine fatalities and 1,247 injuries were associated with machine guarding [1]. Furthermore, between 2000 and 2008, MSHA reported 40 fatalities related to the lockout/tagout of machinery and equipment in both surface and underground operations [2]. Accordingly, NIOSH researchers are investigating an intelligent method of addressing machine guarding issues by verifying that the machine guards are adequately installed during normal operations and that the mining equipment is properly shut down/locked out/tagged out during maintenance-related operations.

Prior NIOSH research revealed that entanglement in surface mining conveyor components was the most common cause of machine-related fatal accidents, accounting for 48% of the recorded fatalities. This research also identified that the worker was performing some form of maintenance or cleanup in 83% of the recorded surface mining machine-related fatalities [3]. Although current protection methods, such as mechanical machine guards and lockout/tagout practices, have provided an elevated form of protection, accidents continue to occur. The development of a more intelligent system is one approach to help ensure that equipment is properly guarded and properly locked out and tagged out during maintenance. This machine guard monitoring system is a part of a more encompassing intelligent system that will integrate proximity detection capabilities to actively track and alert workers in close proximity to hazardous areas and thus reduce machine-related entanglement deaths and injuries.

The first phase in the development of the intelligent system was focused on demonstrating how wireless communication technologies and rugged, dependable sensors could be integrated to remotely monitor mechanical guards. In addition, a conveyor's operational status could be monitored to eliminate hazardous working conditions associated with missing guarding or inappropriate lockout/tagout maintenance procedures. A conveyor was selected as the test bed for this project based on MSHA accident and injury statistics, which identified conveyors as one of the pieces of equipment most commonly involved in machine-related entanglement accidents. The conveyor was outfitted with sensors tasked with wirelessly transmitting the operational and positional status of machine guarding to a computer typically found in a mine operation's control room. This status was transmitted via a wireless access point (WAP) to a controller using an IEEE 802.15.4 wireless communications protocol. The preliminary test results indicated that wireless machine guard monitoring can be performed effectively using an existing wireless data communication system and carefully chosen sensors and switches. This article summarizes the selection and integration of the system components and the control system architecture used.

The conveyor test bed. (Photo courtesy of NIOSH.)

Test Bed

The conveyor for the experimental test bed (Figure 1) was an electrically powered conveyor running a 610-mm-wide belt. This conveyor was obtained from a local mining company's salvage yard. Measures were taken to simulate a conveyor configuration typical of a surface mining operation. Metal brackets were machined to install the conveyor at an approximately 15° slope to simulate a stacking conveyor. The original guards on the conveyor were stripped off to ensure that the guarding package would be compliant with MSHA guarding recommendations [4] as defined in the MSHA Title 30 CFR Parts 56, 57, 75, and 77. The new guarding package was developed in collaboration with Belt Conveyor Guarding in Barrie, Ontario, Canada. Because the head, tail, and idler pulleys account for more than 60% of conveyor accidents [5], the guarding package was designed to include a tailwheel end guard, belly guards, return roller guards, and a return roller basket. A head pulley guard was also constructed in the laboratory. These guards were designed to restrict access to pinch points and hazardous areas of the conveyor during normal operation.

A cable-actuated emergency stop (e-stop) was installed to shut down the conveyor in the event of a malfunction during operation (Figure 2). The e-stop switch's activation status was continuously monitored by a wireless beacon.

A wireless communication system, built by Venture Design Services, Inc. and approved by MSHA for electrical safety, was used as the backbone of the monitoring system. The machine guard monitoring system used the commercially available communications system to transmit data regarding the mechanical and magnetic switches through the repurposed sensor beacons, which is conventionally used to track personnel in a mine environment. These beacons transmitted the status of the guards every 2 s to a WAP.

The magnetically activated reed switches, breakaway switches, and plunger switches were employed to monitor the position of the guards and the e-stop. Each switch was selected based on its installation requirements, ruggedness, and ability to withstand vibrations typical of the conditions at each of the machine guard positions.

A COMMUNICATIONS SYSTEM WAS SUCCESSFULLY EMPLOYED TO TRANSMIT SWITCH AND SENSOR INFORMATION TO A REMOTE LOCATION.

The information from the switches was transmitted to a computer monitor at the end user's location through a Web page provided by a remote subnet controller. The end-user interface can be tailored specifically to a mine operation to display logistic and maintenance-related information, as well as positional data in a Web page format generated by a subnet controller.

Wireless Monitoring System

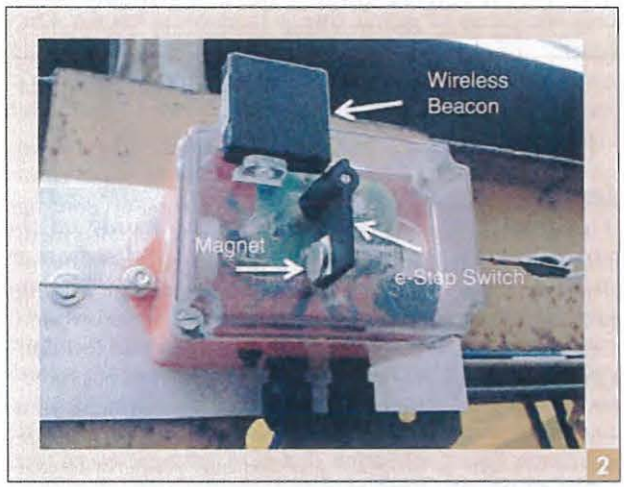
Communications

A wireless communication and personnel tracking system was essential for the intelligent lockout/tagout and guarding monitoring system for use in surface and underground mines. The system selected was Venture Design Services, Inc.'s MineTracer, an MSHA-approved narrow-band wireless mesh network following the IEEE 802.15.4 standard and transmitting at a frequency of 2.4 GHz. It uses powered WAPs with battery backup up to 96 h. The network was designed for text messaging and tracking of miners. Workers wearing active radio frequency identification tags are tracked via the received signal strength indication obtained by WAPs distributed throughout a mine. The MineTracer also has sensor beacons and mobile communicators that transmit data to the WAPs.

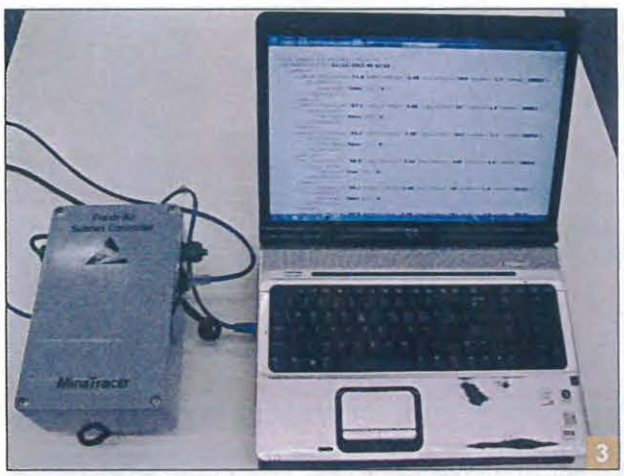
In this article, the sensor beacons were configured to wirelessly transmit the status of the various guards and safety devices. They transmitted the guard sensor switch states as well as the beacon's battery voltage and identification number to neighboring WAPs. These values are updated and retransmitted at the preset intervals, in this case every 2 s. These data are then displayed in the form of a Web page on a control room computer monitor, which is updated by the subnet controller. The beacon's unique identification number is used to determine its precise location and the guard group or device associated with it. The state of sensors monitoring the guards and the e-stop are all displayed on the MineTracer system user interface (Figure 3) in a standard Web page text format. An operator in the control room can note if a guard in a group is in place or removed and if the e-stop is activated. Accessibility to this interface is a beneficial feature of the system as it could potentially be viewed over the local area network on-site or from another remote location using an Internet connection.

Wireless Sensor Beacons

Two different types of beacons were used in the wireless monitoring system and are made by Venture Design Services, Inc. for the commercially available tracking and communications system. Originally developed for use with the MineTracer system, the beacons are offered in both wire-in sensor and built-in sensor designs (Figure 4). Both kinds of beacons were used by NIOSH



A cable-activated e-stop utilizing a built-in sensor beacon to monitor its on/off state. (Photo courtesy of NIOSH.)



A subnet controller and user interface. (Photo courtesy of NIOSH.)

researchers in the wireless guard monitoring system.

The wire-in beacon is designed to accept inputs from user-selected wired sensors, such as the Hamlin reed switches, whereas the built-in sensor beacons have an internal magnetically activated reed switch sensor. The built-in sensor beacons are MSHA approved for underground coal mines, whereas the wire-in sensor beacons are experimental. The different designs facilitate the integration process by providing benefits based on the end user's needs and configuration preferences.

A WIRELESS MACHINE GUARD MONITORING SYSTEM WAS DEVELOPED AND INSTALLED IN A LABORATORY.

To offer a more cost-effective solution, instead of using a beacon for each of the 19 guards on the conveyor test bed, the guards were gathered into five groups: 1) side guards, 2) belly guards, 3) head pulley guards, 4) return idler guards, and 5) return roller baskets. This reduced the number of beacons required from 19 to five. When guard switches are grouped in this manner, the exact guard switch that has been tripped is not known; only the group of guards that is in alarm is known. Once mounted, the wire-in beacons and the built-in beacons successfully transmitted the state of all the sensors or groups of sensors from the conveyor to the simulated control room computer through the WAP and subnet controller.

Sensors

The installation of the system focused mainly on the implementation of mechanical switches and sensors to monitor the guards and safety interventions. Different types of sensors and switches were selected based on their features. Durability, effectiveness, ease of integration, and cost were the major considerations for selecting the sensors for this project. The criteria for evaluation of the switches, mounting hardware, and configurations were the magnetic activation fields, activation distances, plunger travel, and activation force required.

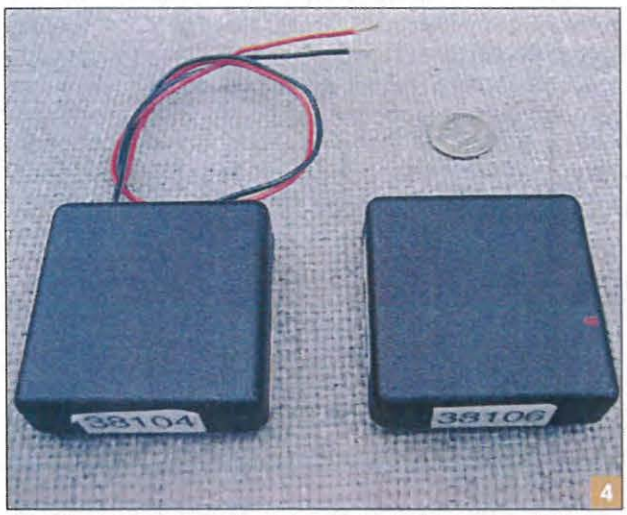
Breakaway Switches

Breakaway switches (Curt Breakaway Switch 12-V dc, model I-2010/52010) were used to monitor the belly guards underneath the belt conveyor (Figure 5). These rugged switches are designed to withstand harsh outdoor environments and are commonly used to activate brakes on a trailer that becomes disengaged from the tow vehicle. The force required to pull the activation key out of the housing ranged from 100 to 110 N. The particular application for these sensors was to monitor the presence of chain-suspended conveyor belly guards and roller baskets.

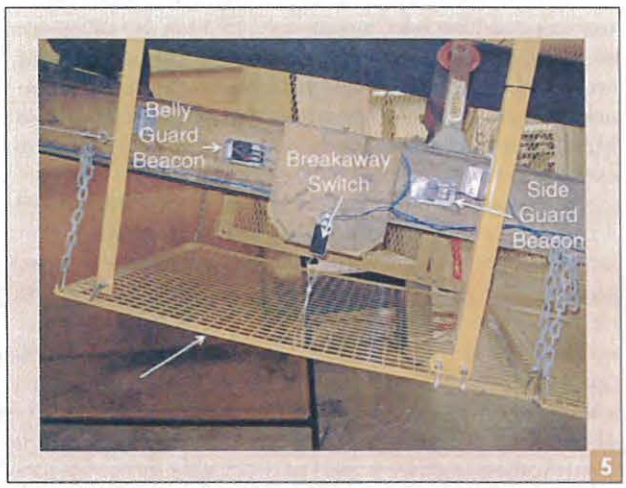
Breakaway switches were mounted to the belly guards by fastening the activation key to the belly guard and the housing to a support member. The belly guards are gravity hung from the conveyor with chains. To remove the guard, the breakaway activation keys must be pulled from their housing. The breakaway switches were also used to monitor the presence of the return roller basket (Figure 6). This was primarily done to monitor whether or not the basket was replaced after maintenance and the sensors reconnected.

Plunger Switches

Idler guards were installed for protection against entanglement in the rollers. Plunger switches were used to monitor whether doors on these hinged return idler guards were open or closed (Figure 7). The doors of these guards have a small, relatively tight fit. The plunger switches used were the Bernstein model D-32457 ENK-SU1Z iw 608.1152.007 (from Warner Electric). The breakaway activation distances vary from 1 to 3 mm depending on the mounting configuration used. The activation force required for these units ranges from 8 to 9.2 N, and the total plunger travel is 5.6 mm.



The wire-in sensor and built-in reed switch beacons. (Photo courtesy of NIOSH.)



The belt conveyor side guards are removed to expose the sensor beacons and the belly guard breakaway switch locations. (Photo courtesy of NIOSH.)

The breakaway switch (center) attached to a return roller catch basket. (Photo courtesy of NIOSH.)

The plunger switch installed on a return idler pulley guard. (Photo courtesy of NIOSH.)

Magnetic Reed Switches

Magnetic reed switches were evaluated for use on side guards and as an alternative to plunger switches on the return pulley guards. An initial concern was that mechanical guard switches could be easily broken when taking the guards on or off and that they may quickly be fouled with rock dust contamination. The reed switches provided the solution to keep the switch out of harm's way because of the ability to implement a gap between the actuating magnet and the reed switch. A 50-mm gap was used in the mounting configuration to reduce the likelihood of damage from impact and increase the resistance to fouling.

The magnetically activated reed switch sensors selected consisted of a cylindrical stainless steel threaded body, output wiring, and mounting nuts (Hamlin model 59075-1-U-03-A-ND). These sensors are commonly used for off-road vehicles. Shock resistance testing was conducted using a laboratory vibrations platform to determine that these sensors can withstand a 40-G shock load.

A nonstandard magnet was required to increase the activation distance from 19 mm, using the switch manufacturer's recommended magnet, to 50 mm. Several magnet types were evaluated along with a button magnet for the tight-fitting return idler guard doors. Since the magnetic fields of permanent magnets vary, general guidelines regarding activation distances were established for three different types of magnets. The magnets were mounted opposite these reed switches at varying offset distances and misalignments to determine the optimal mounting for switch activation.

The magnetic activation field is defined as the region surrounding the magnet in which the normally open magnetic reed switch closes. It is important to determine this for each magnet so that the maximum standoff distance and misalignment allowance can be determined. The three types of magnets investigated varied in dimensions and pulling force, as shown in Table 1.

A protocol was developed to explore the activation distances and misalignment thresholds using a test fixture built in the laboratory to ensure repeatability and accuracy of measurements. The test fixture consisted of a milling machine, a reed switch sensor mounted in an aluminum holder and placed in the mill's chuck, a selected magnet, and a device to indicate when the reed switch was triggered (Figure 8). Placement of the magnet directly on the

TABLE 1. MAGNET SPECIFICATIONS.

Magnet Type	Type	Pull Force (N)	Diameter/Height (mm^2)	Maximum Average Activation Distance (mm)
A) Button magnet	Neodymium, sealed	28.9	17.78 × 2.8	22.9
B) Mounting magnet	Neodymium, sealed	845.1	50.8 × 12.7	71.1
C) Mounting magnet	Ferro magnet, unsealed	422.6	76.2 × 10.9	76.2

steel fixture simulated the mounting of the magnet on a steel guard.

A reed switch closure indicator was designed and built to trigger a red light-emitting diode (LED) when the magnetic field activated the magnetic reed switch. This indicator was used to determine activation distances for three magnets and also to map the activation fields of those same magnets. The coordinates were acquired using the digital readout on a milling machine, which controlled the movement of the reed switch assembly.

For the linear activation distance, the stainless steel reed switch was lowered until it touched the magnet. The digital readout was zeroed. The reed switch was then raised out of the magnet's magnetic field and then slowly lowered until the LED turned on. That distance was then recorded.

Mapping the magnetic activation field was done by repeating the above procedure after incrementally offsetting the reed switch. Once the digital readout was zeroed and the reed switch withdrawn from the magnet's magnetic field, the reed switch was laterally shifted in 5.1-mm increments and the test was repeated. These coordinates were plotted, and the resulting graph defined the magnet's maximum magnetic activation field.

THE SENSOR BEACONS WERE CONFIGURED TO WIRELESSLY TRANSMIT THE STATUS OF THE VARIOUS GUARDS AND SAFETY DEVICES.

One of the mapped activation fields can be seen in Figure 9, where the magnetic activation field is defined by the region where the magnetic field lines are strong enough to activate the reed switch. The maximum height of the activation field was 71.8 mm and occurred when there was no lateral offset. The average maximum linear activation distances were determined to be: 1) 22.9 mm for magnet A, 2) 71.12 mm for magnet B, and 3) 63.5 mm for magnet C (Table 1).

The results of the permanent magnet testing revealed that the maximum lateral (side-to-side) misalignment activation distance is ~2/3 the maximum linear activation distance for the permanent disc-shaped mounting magnets used.

Another experiment conducted was designed to explore the effects of the buildup of metal cuttings on the magnet. This was of particular interest from a reliability standpoint to prevent false alarms or no alarms due to changed magnetic fields. The experiment was conducted to determine how much the magnetic activation fields of each type of magnet would diminish if they were fully loaded with metal filings. The results suggest that the magnetic activation fields of the disc-shaped mounting magnets tested were reduced by ~1/3 of their standard field size.

A 50-mm standoff gap between the reed switches and type B magnets was configured on all the side guards of the conveyor test bed (Figure 10). The standoff between the reed switches and type A button magnet on the closed return roller guard doors was set at a 3.2-mm gap (Figure 11).

The potential for misalignment due to impact and the buildup of cuttings on the magnets may result in a more conservative mounting gap preference. This change can be

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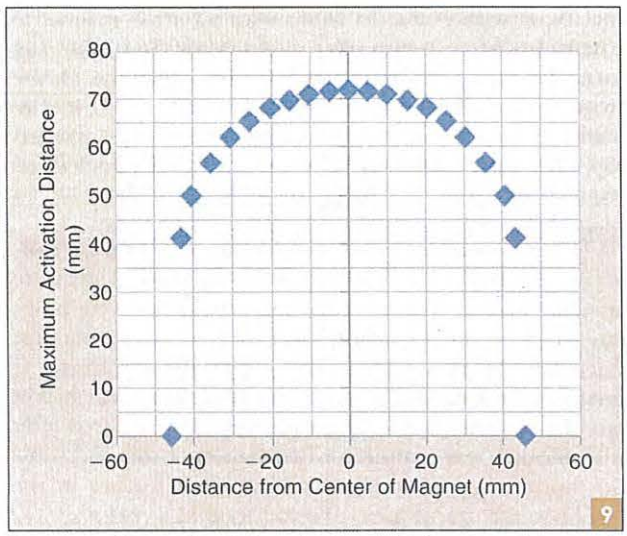
The reed switch activation text fixture. (Photo courtesy of NIOSH.)



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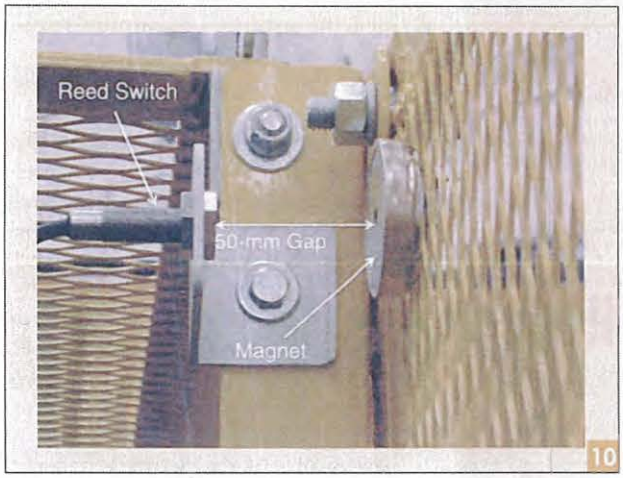
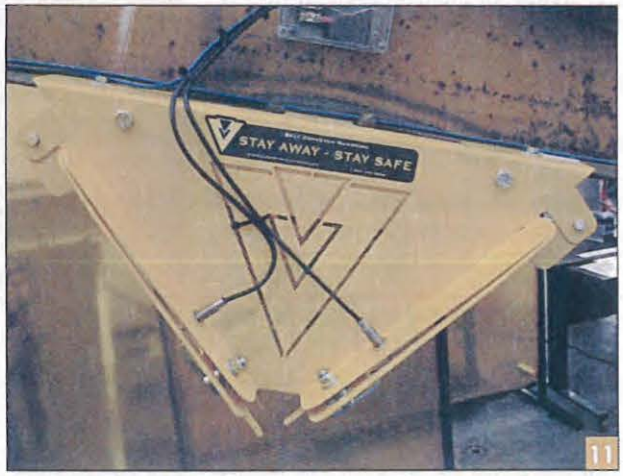
The magnetic reed switch activation field for a type B magnet.



The side guard standoff distance set at 50 mm. (Photo courtesy of NIOSH.)



The return idler guard equipped with magnetic reed switches. (Photo courtesy of NIOSH.)

made using the reed switch's threaded body, which has a 25-mm adjustment range capability. The recommended maintenance for this installation would include routinely cleaning the magnets with a plastic or aluminum spatula and checking the alignment to ensure proper activation distances.

Conclusions

A wireless machine guard monitoring system was developed and installed in a laboratory setting with considerations being made for the implementation in a real-world environment. Measures were taken to design a rugged and accurate system to prevent false alarms.

A communications system was successfully employed to transmit switch and sensor information to a remote location. The Web-based interface provided an accessibility advantage for monitoring the system from virtually any location and potentially monitoring many conveyors from a central interface.

In this article, magnetic field activation maps and vibrations tests were essential in developing a practical system that provided accurate monitoring capabilities of machine guards on a belt conveyor. The results suggest that mine-specific installation considerations may dictate magnet strength needed to effectively and accurately trigger the magnetic reed switches as well as the sensitivity of the switches used. Belly guard breakaway sensors could also be modified so that less force is required to pull the activation key out of the housing. However, the 100–110 N of required force can be difficult to apply given the confined spaces where some of these belly guards are mounted.

This monitoring system would not only provide conveyor guarding status but could also be used to generate alarms based on whether guarding procedures were properly followed during maintenance and normal operations. For example, this system would provide a warning if guards were removed prior to shutting down and lockin out the conveyor or if the guards were not replaced after maintenance was completed. Installation of this and similar monitoring systems can add another feature in the automatic protections against traumatic, machine guarding-related injuries. While the laboratory experiments performed here were limited to a belt conveyor application, there are numerous potential applications of the system to other machinery or equipment.

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