DEVELOPMENT OF A NEW EMERGENCY STOP SWITCH TO ASSURE AN OPERATOR’S SAFETY AGAINST FORESEEABLE FAILURE
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Abstract
Ensuring an operators’ safety is of prime importance in HMI (Human Machine Interface) environments. For an operator faced with an emergency situation, using emergency stop switches is the last possible measure to avoid accidents. Thus emergency stop switches must send a stop command to machines and systems without failure. Many international standards have been written to ensure emergency stop switches meet both functional and structural requirements. We have discovered, however, the structure of conventional emergency stop switches cannot shut down system operations when improperly installed or operated with an excessive amount of force. This paper explains the design of the next-generation emergency stop switches, which achieve a safer HMI environment and changes the concept of emergency stop switches.

Introduction
In HMI (Human Machine Interface) environments, where humans and machines interact, such as an automatic production system using industrial robots, we need to develop machines and systems that ensure an operator’s safety. The issuance of ISO 12100 (Safety of machinery-Basic concepts, general principles for design) in 2003 increased the awareness of safety in the manufacturing industry [1, 6-11]. This standard requires machine designers and manufacturers to remove or reduce risks to a tolerable level by way of inherent safety design, and to provide safeguarding measures to residual risk [12]. An emergency stop switch, which sends a stop command to a machine, is one of the safeguarding measures. International safety standards such as ISO 13850 and IEC 60947-5-5 provide strict structural requirements for emergency stop switches [2-5]. The strict requirements reflect the importance of emergency stop switches, which must send stop commands to machines in any situation, without failure.

Upon performing an FMEA (Failure Mode Effects Analysis) on emergency stop switches compliant with international standards, we have found that conventional emergency stop switches do not stop machine operation when they are improperly installed or excessive shock is applied – resulting in the failure of

Figure 1. Installation of Emergency Stop Switches on Machine System
emergency stop switches. FMEA is a method that examines potential failure modes and their effect, in order to help prevent failures from occurring. In this paper, we report on new emergency stop switches and the world’s first safety features, developed through in-depth analysis of an operator’s foreseeable misuse of these emergency stop switches [13].

Safety of Emergency Stop Switches upon Failure

Because international safety standards such as ISO 12100 require emergency stop switches to be installed in the vicinity of an operating area, a manufacturing environment as shown in figure 1 is equipped with many emergency stop switches. All emergency stop switches are designed with NC (normally closed) contacts. A NC contact is closed (ON) normally, and opens (OFF) when the actuator of the contact operates. Therefore, an emergency stop switch sends a stop signal to the machine when pressed, with the NC contacts shifting from a closed status to an open status.

An emergency stop switch fulfills its role when it is installed and operated properly. However, we have discovered through FMEA, that conventional emergency stop switches might fail in a hazardous mode, sending no stop signals to machines when they have been installed improperly or they have been subjected to excessive shock. An operators’ safety, obviously, would be severely jeopardized. Conventional emergency stop switches, used around the world, can hardly claim to be the optimum choice of a human machine interface, and further efforts for technological innovation are necessary.

Failure due to excessive shock

Emergency stop switches are, as the name suggests, are frequently used in emergency situations unlike other pushbuttons. In addition, they are more likely to be operated in highly tense situations. Because emergency stop switches can be operated with an extreme level of force, they must satisfy the requirements of IEC 60947-5-5, 7.7.3 (Impact test for button type actuators) that stipulates a shock testing method. However, in real-world applications, a much greater impact can be placed upon emergency stop switches.

For example, when an operator is working with a hammer, as shown in figure 2, and suddenly faced with an emergency situation, the operator may mistakenly hit the emergency stop switch using the hammer. Also, an operator might mistakenly drop a teaching pendant, on which an emergency stop switch is installed, as shown in figure 3. In both cases, the emergency stop switches are exposed to a great deal of shock. Because emergency stop switches are mostly made from plastic parts that cannot stand extreme levels of shock, parts can be damaged when a great shock is applied. The NC contacts of inoperative emergency stop switches tend to remain ON (closed), thus causing possible danger to operators since this machine can no longer be stopped.

Figure 2. Excessive shock on the operator part by using a hammer

Figure 3. Excessive shock on the operator part due to dropping a teach pendant
Failure due to improper installation

Most emergency stop switches are separate type, which consist of a separate operator part and contact block. With these emergency stop switches, detaching the contact block turns on the NC contacts (closed). This does not cause a problem during installation and maintenance when the operator part and contact block are connected firmly and operated properly as shown in figure 4 (a). However, in the case of an improper connection as shown in figure 4 (b), the contact block may become detached from the operator part due to impact or vibration during operation. Because a machine operator cannot visualize the failure of an emergency stop switch by looking at it installed on a control panel, pressing the emergency stop switch does not stop machine operation, imperiling the safety of the operator. In figure 4 (b), the contact block is exaggeratedly separated from the operator part for easier recognition of the readers.

Safety-ensuring structure of emergency stop switches

There has been an evolution in separate-type emergency stop switches, and we have compared the structures and features developed in 1970’s (1st generation), 1990’s (2nd generation), and 2000’s (3rd generation), as explained in greater details later in this paper. The following paragraphs explain the structural problems of 2nd-generation emergency stop switches, shown in figure 5 (a), and the solution realized in 3rd-generation switches shown in figure 5 (b).

Safety structure against shock

When a 2nd-generation emergency stop switch is in its normal status (a1), the NC contacts are closed (a2) by use of a spring (a3). When latched (a4), the contacts are opened (a5) by a push rod and the spring
is pressed (a6). Therefore, the potential energy on the NC contacts is high when the switch is latched and low in the normal status (a7). Since energy is always inclined to shift from high to low, the NC contacts in 2nd-generation emergency stop switches (when parts are damaged due to excessive shock) are prone to turn on (closed) causing possible danger to operators because the emergency stop switch can no longer stop machines. Also, the NC contacts always turn on (a8) when excessive shock detaches the contact block from the operator part.

When a 3rd-generation emergency stop switch is in its normal status (b1), the NC contacts are closed (b3) being lifted by a cam, and the spring (b2) is pressed. When latched (b4), the contacts are opened (b6) by a push rod, and the spring is released (b5). Therefore, the energy level on the NC contacts is high in the normal status and low when latched (b7). This energy shift is opposite from the energy shift of 2nd-generation emergency stop switches. Also, the NC contacts turn off (b8) when the contact block is detached from the operator part, stopping machines and therefore ensuring an operator's safety. This original, world's first mechanism greatly improves the safety of emergency stop switches.

Safety structure against detached contact blocks
As explained above, when a contact block is detached from a 2nd-generation emergency stop switch, the NC contacts turn on, causing possible danger to an operator. Our 3rd-generation emergency stop switch is designed to forcefully open the NC contacts when the contact block is detached. Even if the contact block comes off when the contacts are welded, the NC contacts turns off without failure, stopping the machine operation. This original, world's first structure has proudly been named Safe Break Action.
The failures and safety modes of both 2nd-generation and 3rd-generation emergency stop switches are described in table 1. The switches are evaluated on safety-ensuring capability in normal status, when the operator part is damaged due to excessive shock, and when the contact block is detached due to improper installation. As the table shows, both switches provide safety when they are in good condition (2A and 3A).

**Table 1. Comparison of Safety between 2nd-generation and 3rd-generation Emergency Stop Switches**

<table>
<thead>
<tr>
<th></th>
<th>Failure</th>
<th>Can the failure be recognized by looking at the operator part?</th>
<th>NC Contact Output when the operator is pressed</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2nd Generation</strong></td>
<td>2A Normal</td>
<td>No failure</td>
<td>N/A ON OFF</td>
<td>Safe</td>
</tr>
<tr>
<td></td>
<td>2B Damaged Operator Part</td>
<td>Cracks on the operator</td>
<td>Yes ON OFF</td>
<td>Safe</td>
</tr>
<tr>
<td></td>
<td>2C</td>
<td>Operator is detached.</td>
<td>Yes Not operative OFF to ON</td>
<td>Hazardous</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>Contact block is detached.</td>
<td>No OFF OFF</td>
<td>Extremely Hazardous</td>
</tr>
<tr>
<td><strong>3rd Generation</strong></td>
<td>3A Normal</td>
<td>No failure</td>
<td>N/A ON OFF</td>
<td>Safe</td>
</tr>
<tr>
<td></td>
<td>3B Damaged Operator Part</td>
<td>Cracks on the operator</td>
<td>Yes ON OFF</td>
<td>Safe</td>
</tr>
<tr>
<td></td>
<td>3C</td>
<td>Operator is detached.</td>
<td>Yes Not operative ON to OFF</td>
<td>Safe</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>Contact block is detached.</td>
<td>No OFF OFF</td>
<td>Safe</td>
</tr>
</tbody>
</table>

When the operator part is damaged and cracked (2B and 3B), the damage can easily be recognized by the machine operator and thus safety can be ensured by simply replacing the switches.

When the operator and internal part are detached from the contact block (2C and 3C), both problems can be recognized, however, 2C does not ensure safety, because the contacts remain on. 3C, on the other hand, provides safety with the contacts opening.

When the contact block is detached from the operator part (2D and 3D), the problem is not recognizable in both cases, because the contact block is behind the panel. The 2D contacts remain closed when the operator part is pressed, jeopardizing the machine operator’s safety, while 3D ensures safety by opening the contacts. The 3rd-generation emergency stop switches, therefore, can claim as having achieved a high level of safety.
The 3rd-generation Emergency Stop Switch and Its Features

Because international safety standards are revised every few years and new standards are also issued to reflect up-to-date safety concepts, manufacturing industries around the world are using both compliant and non-compliant emergency stop switches to the latest safety standards. Table 2 shows the history of international safety standards for emergency stop switches, and a comparison of the characteristics of the 1st, 2nd, and 3rd generation emergency stop switches.

Table 2. History of International Safety Standards and Emergency Stop Switches

<table>
<thead>
<tr>
<th>Year</th>
<th>1990</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Appearance</strong></td>
<td><img src="image" alt="1st Generation Switch" /></td>
<td><img src="image" alt="2nd Generation Switch" /></td>
</tr>
<tr>
<td>Direct Opening Action</td>
<td>Some</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety Lock Mechanism</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Safe Break Action</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Safety when operator is detached</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety when contact is detached</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Failure on safe side when extreme shock is applied</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

The 1st-generation emergency stop switches were developed before international safety standards were issued. Since they lack direct opening action in the contacts and do not have safety lock mechanism, a mechanism to be detailed later in this paper, these switches should no longer be used as emergency stop switches.

The 2nd-generation emergency stop switches are designed to comply with the latest international safety standards, however, they do not take into account the failures caused by human errors explained above. Therefore these switches depend on the strength of their components against shock, and no consideration has been taken regarding the detachment of contact blocks due to installation errors. Emergency stop switches with integrated operator part and contact blocks have been developed (unibody design), however, they also depend only on the strength of their components against shock.

Emergency stop switches which are compliant with standards are, when properly installed and operated, are generally free from problems. However, as argued above, we have to pay attention to the fact that humans will make mistakes and that emergency stop switches may be hit with excessive force, or may be
installed improperly, resulting in detached contact blocks. The 3rd-generation emergency stop switches, while complying with safety standards, provide superior safety against foreseeable human errors. These are the world’s first emergency stop switches to ensure the highest level of safety when compared with other switches.

The requirements of international safety standards for emergency stop switches and other superior designs incorporated in the 3rd-generation emergency stop switches are described below.

- **Direct Opening Action (IEC 60947-5-1; Annex K)**
  A push rod made of a non-resilient material (e.g. unlike spring), directly opens even welded contacts, shutting off the circuit without failure [8,11].

- **Safety Lock Mechanism (ISO 13850; 4.4.4)**
  Once an operator part of an emergency stop switch is pressed and latched, the NC contacts open, and the condition is maintained until the switch is reset. We call this Safety Lock Mechanism. This prevents unexpected restarting or stopping of machines [8,11].

- **Panel Mounting Structure (IEC 60947-5-5; 6.3.2)**
  The 1st-generation emergency stop switches were removable from the front of the panel, and the operator part could fall off due to machine vibration and shock. The 3rd-generation emergency stop switch is installed on the panel from the rear and secured using locking nuts that cannot be removed from the panel front.

- **Reset Method (IEC 60947-5-5; 6.3.1)**
  Emergency stop switches use either turn-to-reset or pull-to-reset methods for resetting, and having emergency stop switches of two types in a workplace can be confusing to the machine operators. Our 3rd-generation emergency stop switches can be reset by both turning and pulling, thereby removing any confusion of the machine operator.

- **Dual Contacts and Dual Circuits in Compact Size**
  As machines are becoming smaller and smaller, the components on the machines must also reduce in size. In the meantime, users are becoming more and more interested in ensuring safety, and they are introducing machines which comply with category 3 or 4 of ISO 13849-1. Achieving the high level of safety often requires employment of emergency stop switches which have dual NC contacts and monitor contact, thereby requiring three to four contacts in one emergency stop switch. A maximum of four contacts are available with our 3rd-generation emergency stop switches, and they have the shortest depth behind the panel for four-contact types. The compact emergency stop switches allow size reduction of control panels and teaching pendants. Teaching pendants, especially, become more user-friendly by lightening their weight.

- **Operator style for the emergency stop switches on teaching pendants**
  When a teaching pendant equipped with an emergency stop switch is accidentally dropped on the floor, the emergency stop switch might receive all the impact. International standards such as IEC 60204-1 require the operator part to be shaped in palm or mushroom style for easy operation. We have discovered, through in-depth analysis, that mushroom-shaped operator part with a sharp convex surface, induces a strong impact on just one part, and the operator is badly disfigured. The disfigured operator part can result in damage of the switch’s internal parts. To solve this problem, we flattened the convex shape some degrees, and this flat-type mushroom operator part is less likely to become disfigured when dropped on the floor, greatly reducing the impact on the internal parts of the switch. Our 3rd-generation emergency stop switches are designed with a flat-type mushroom operator part. This design, which also conforms to palm-style requirements, perfectly complies with international safety standards and has proved to be easy to operate and structurally safe.
Padlocking type

Emergency stop switches are installed in many applications, and in some of these applications many operators operate an emergency stop switch. When there is an operator working in a hazardous area, where machines are temporarily stopped by pressing the emergency stop switch, the switch must not be reset if there is an operator still working in the area. To prevent the switch from mistakenly being reset, we have developed an emergency stop switch on which a padlock can be installed. This padlock-type emergency stop switch, when latched, allow machine operators to install a padlock. Resetting the switch is only possible when the padlock is removed. In addition, multiple padlocks can also be installed on this switch by means of a hasp [14].

The 3rd-generation emergency stop switches, which we developed with the new safety concept shown in figure 5, have been realized as on-market products. The 16-mm XA series, 22-mm XW series, and 30-mm XN series have already been installed in various machines and used in many applications, enjoying a high reputation as having contributed to the improvement of safety.

Conclusion

In this paper, we reported on the importance of ensuring safety when emergency stop switches are damaged due to operators’ erroneous operations, and also the excellent performance of our newly developed emergency stop switches. Requirements of current international safety standards ensure operators' safety when emergency stop switches are properly operated and installed, however, they can not be claimed as being sufficient when emergency stop switches fail.

In future manufacturing industry, the importance of safety concepts to ensure safety against human errors and failures of components will become widespread. We will be committed, as we have been so far, to the improvement of safety and usability of safety components.

Acknowledgements

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Reference

[3] IEC60204-1 Ed. 4.1; (2000), Safety of machinery - Electrical equipment of industrial machines - Part1: General requirements
[4] IEC60947-5-1 Ed. 3.0; (2003), Low-voltage switchgear and controlgear. Part5-1: Control circuit devices and switching elements - Electromechanical control circuit devices
[5] IEC 60947-5-5 Ed.1.1; (2005), Low-voltage switchgear and controlgear - Part 5-5: Control circuit devices and switching elements - Electrical emergency stop device with mechanical latching function


