

Human Machine Interface (HMI) Design: The Good, The Bad, and The Ugly (and what makes them so)

Paul Gruhn, P.E.

ICS Triplex | Rockwell Automation, Houston, TX

paulg@icshou.com, 713-353-2417

Abstract

Poor HMI designs have been identified as factors contributing to abnormal situations, billions of dollars of lost production, accidents, and fatalities. Many HMIs actually impede rather than assist operators. Many of the poor designs are holdovers due to the limitations of early control systems and the lack of knowledge of system designers. However, with the advent of newer and more powerful systems, these limitations no longer apply. Also, decades of research has identified better implementation methods. Unfortunately, change is difficult and people continue to follow poor design practices. In fact, some new designs are actually *worse* than older designs! Just as a computer is not a typewriter, new HMI designs should not mimic those of old. The problem is that many designers often simply don't know any better. This presentation will review *why* certain HMI designs are poor (with many examples) and show how they can be improved.

A Comparison

People are naturally proud of whatever they produce, whether it's something as simple as a menu, or as potentially complicated as an HMI. It's their baby and they love it, no matter what anyone else may think! Unfortunately, many people don't know what they don't know. As a result, they're incapable of judging against established criteria; they've never been educated or trained on the subject at hand.

For example, when desktop publishing first became available to the masses on personal computers, the result was a flood of very poorly designed newsletters and other printed materials. People were producing documents without any knowledge of or training in graphic design.

Figure 1 is a reproduction of an actual restaurant menu. No doubt the restaurant owner thought he did a wonderful job. Hopefully his cooking skills are better than his graphic design skills!

Good graphic design can be distilled down to four simple and basic concepts:

1. **Contrast:** Things that are different should look *very* different.
2. **Repetition:** Repeat visual elements.
3. **Alignment:** Every element should have some visual connection with another.
4. **Proximity:** Things that belong together should be placed together; those that are different, should not.

These four concepts are very easy to remember using an acronym based on the first letter of each of the four words. (Sorry!) Utilizing those four simple rules results in the menu shown in Figure 2. Which do you think is easier to read? Which gives a better image of the establishment? These concepts can also be used when designing HMIs!

Gertrude's Piano Bar	
STARTERS:	
GERTRUDE'S FAMOUS ONION LOAF - 8	
GAZPACHO OR ASPARAGUS-SPINACH SOUP - 7	
SUMMER GARDEN TOMATO SALAD - 8	
SLICED VINE-RIPENED YELLOW AND RED TOMATOES WITH FRESH MOZZARELLA AND BASIL BALSAMIC VINAIGRETTE	
HAMLET'S CHOPPED SALAD - 7	
CUBED CUCUMBERS, RADISHES, AVOCADO, TOMATOES, JARLSBERG CHEESE, AND ROMAINE LEAVES TOSSED IN A LIGHT LEMON VINAIGRETTE	
CAESAR SALAD - 7	
HOUSE-MADE DRESSING, PARMESAN AND CROUTONS	
CARIBBEAN CEVICHE - 9	
LIME-MARINATED BABY SCALLOPS WITH RED PEPPER, ONIONS, CILANTRO, JALAPENOS, AND ORANGE JUICE	
SHRIMP COCKTAIL - 14	
FIVE LARGE SHRIMP WITH HOUSE-MADE COCKTAIL SAUCE	
ENTREES:	
NEW YORK STEAK, 16 OZ - 27	
ROTISSERIE CHICKEN - 17	
FRESH FISH, 10 OZ - MARKET PRICE	
GRILLED SHRIMP - 24	
NEW ORLEANS LUMP CRAB CAKES WITH WARM VEGETABLE COLESLAW, MASHED POTATOES, SPINACH AND ROMESCO SAUCE - 18	
GRILLED PORTOBELLO MUSHROOM STUFFED WITH RICOTTA CHEESE, GARLIC, ONIONS AND SPINACH, SERVED OVER MASHED POTATOES - 18	
NEW ZEALAND RACK OF LAMB - 26	
BARBEQUED BABY BACK RIBS - 24	
AUSTRALIAN LOBSTER TAIL, 10 OZ - MARKET PRICE	
SURF & TURF	
AUSTRALIAN LOBSTER & 8OZ FILET - MARKET PRICE	

Figure 1: Original Menu
(Source: The Non-Designers Design Book)

Gertrude's Piano Bar	
Starters	
Gertrude's Famous Onion Loaf	8
Gazpacho or Asparagus-Spinach Soup	7
Summer Garden Tomato Salad	8
<i>sliced vine-ripened yellow and red tomatoes with fresh mozzarella and basil Balsamic vinaigrette</i>	
Hamlet's Chopped Salad	7
<i>cubed cucumbers, radishes, scallions, avocado, tomatoes, jarlsberg cheese, and romaine leaves tossed in a light lemon vinaigrette</i>	
Caesar Salad	7
<i>house-made dressing, Parmesan, and croutons</i>	
Caribbean Ceviche	9
<i>lime marinated baby scallops with red pepper, onions, cilantro, jalapenos, and orange juice</i>	
Shrimp Cocktail	14
<i>five large shrimp with house-made cocktail sauce</i>	
Entrees	
New York Steak, 16 ounce	27
Rotisserie Chicken	17
Fresh Fish, 10 ounce	Market Price
Grilled Shrimp	24
New Orleans Lump Crab Cakes	18
<i>with warm vegetable coleslaw, mashed potatoes, spinach, and romesco sauce</i>	
Grilled Portobello Mushroom	18
<i>stuffed with ricotta cheese, garlic, onions and spinach, served over mashed potatoes</i>	
New Zealand Rack of Lamb	26
Barbequed Baby Back Ribs	24
Australian Lobster Tail, 10 ounce	Market Price
Surf & Turf: Australian Rock Lobster & 8 ounce Filet	Market Price

Figure 2: Redesigned Menu

Principles for User-Centered Design

More data does not equal more information. The information displayed should not center on the sensors and technology that produce it. A proper user-centered design should integrate the information in ways that fit the goals, tasks and needs of the user.

User-centered design can be achieved through the following principles and practices.

- **Organize technology around the user's goals, tasks and abilities.** Task analyses need to be conducted to check if the system provides the needed information.
- **Organize technology around the way users process information and make decisions.** People first act to classify and understand a situation. Experts use pattern matching to draw upon long-term memory in order to quickly understand a situation. Decision makers must do more than simply perceive the state of their environment in order to have good situation awareness. They must understand the integrated meaning in light of their goals; they must understand the situation as a whole.
- **Keep the user in control and aware of the state of the system.** High levels of automation can actually put users out-of-the-loop leading to low levels of situation awareness. If their awareness is compromised, their ability to be an effective decision maker is also compromised.

Situation Awareness (SA)

Situation awareness means a) being aware of what is happening around you, b) understanding what that information means to you now, and c) understanding what that information means to you in the future. Situation awareness relates to the goals and objectives of a specific job or function.

Situation awareness consists of the following three levels.

1. **Perception of needed data.** The status, attributes and dynamics of elements in the environment.
2. **Comprehension of the current situation.** Comprehension is based on a synthesis of the disjointed Level 1 elements and a comparison of that information against one's goals. Novices may not have the knowledge base to draw on and may be at a disadvantage when trying to develop Level 2 SA.
3. **Projection of future status.** The ability to predict what will happen. This can only be achieved by having a good understanding of Level 2 SA, along with a highly developed mental model of the system.

By understanding how operators select and use goals, designers can better understand how information is perceived. Without understanding the user's goals on SA, the information presented has no meaning.

Demons of Situation Awareness

Situation awareness depends upon human information processing which is a complex process. Factors that undermine SA are referred to by Endsley et al as 'demons'. They consist of the following.

1. **Attention tunneling.** Fixating on one set of information to the exclusion of others. This is the most common type of SA failure.
2. **Working memory trap.** Relying on limited short term memory.
3. **Workload, anxiety, fatigue, and other stressors.** Reduction in a person's capacity to process information.
4. **Data overload.** Overwhelming amounts of data can reduce SA. For example, text moves through our mental pipeline much more slowly than information presented graphically.
5. **Misplaced salience.** Salience is the compellingness of certain forms of information. The color red, movement, and flashing lights can distract a person away from information that may be more important.
6. **Complexity creep.** It's difficult to develop an accurate mental model of how a system works when there are too many features.
7. **Incorrect mental models.** Using the wrong mental model will lead to misinterpretation of information.
8. **Out-of-the-loop syndrome.** Automation can actually undermine SA by taking people out-of-the-loop. They may develop poor SA on how the automation is performing, as well as the elements the automation is supposed to be controlling.

Typical Practice in the Process Industry

Unfortunately, many HMIs are developed with little user input. Many users do not have an HMI design guideline. This means every HMI they receive on every project will be different. This lack of standardization will naturally cause problems. Many HMIs are created by white collar, college educated engineers; yet the systems are used by blue collar, high school educated operators. The mental models used by engineers and operators differ. Operators are not asked what their goals are, how they're expected to operate the plant efficiently, or what information they need in order to do that. Most HMI screens are based on P&IDs (Piping and Instrumentation Drawings) and animated with live data (fields with numbers). This is Level 1 SA. This generally does not provide the operator with the relevant information he needs in order to understand how the plant is operating (Level 2 SA) or how it may be trending (Level 3 SA). The result is HMIs like the one shown in Figure 3.

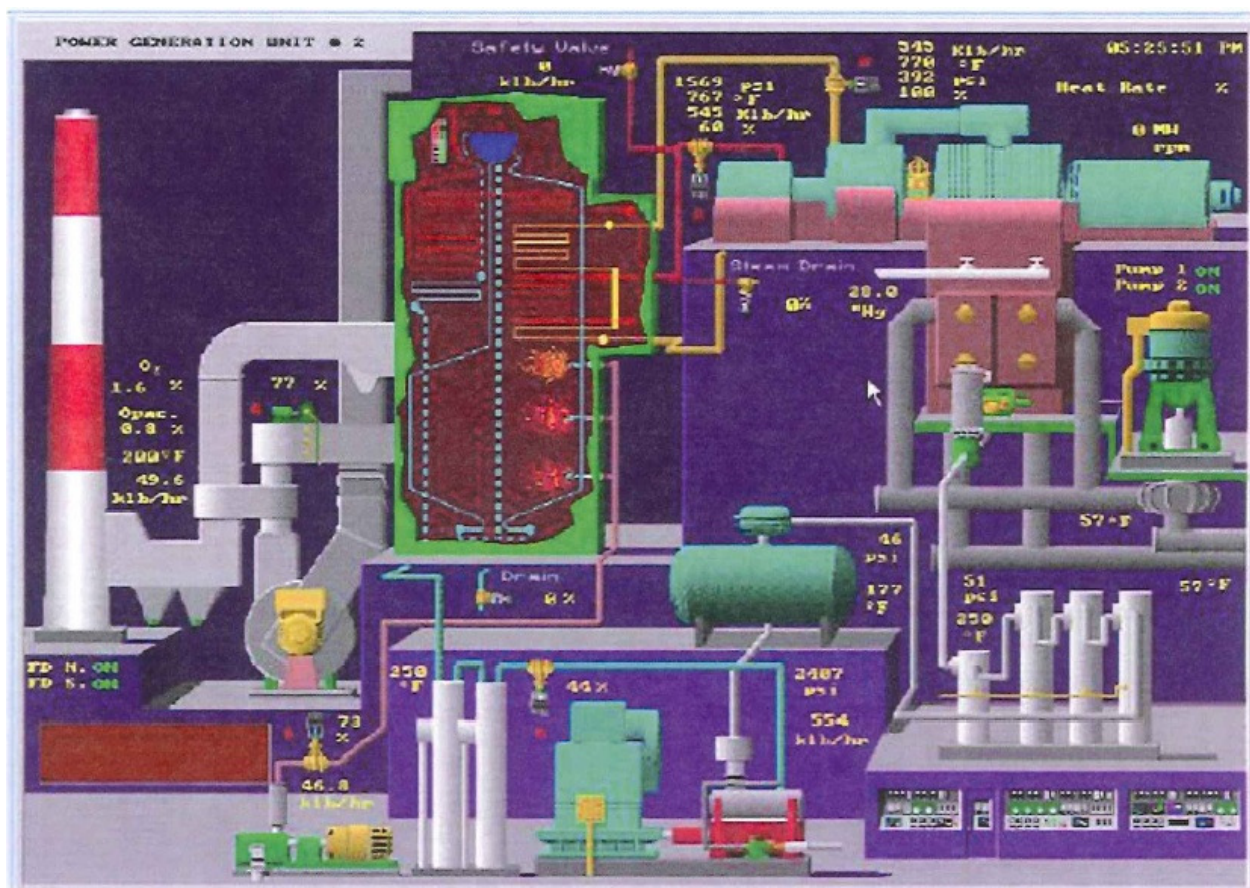


Figure 3: A Poor HMI (Source: The High Performance HMI Handbook)

In many such HMIs fan and pump impellers are spinning, flames are animated, valves that are open and pumps that are on are shown in one color, valves that are closed and pumps that are off are shown in another. Different process lines are shown in different colors. The overuse of animation and color results in misplaced salience. Raw data (not useable Level 2 information) is presented in many different fields. Too much raw data results in both working memory trap problems and data overload. Just what *should* all the values be? How can this data be turned into

usable information (e.g., is the plant running optimally)? How can this information be projected into the near future (e.g., are we approaching any alarm or trip levels)? What level of experience and training are required for someone to have a correct mental model of the system?

More recent guidelines stress the use of low contrast gray backgrounds and limited use of color. Some designers still violate the basic principles and screens such as the one shown in Figure 4 continue to be produced.

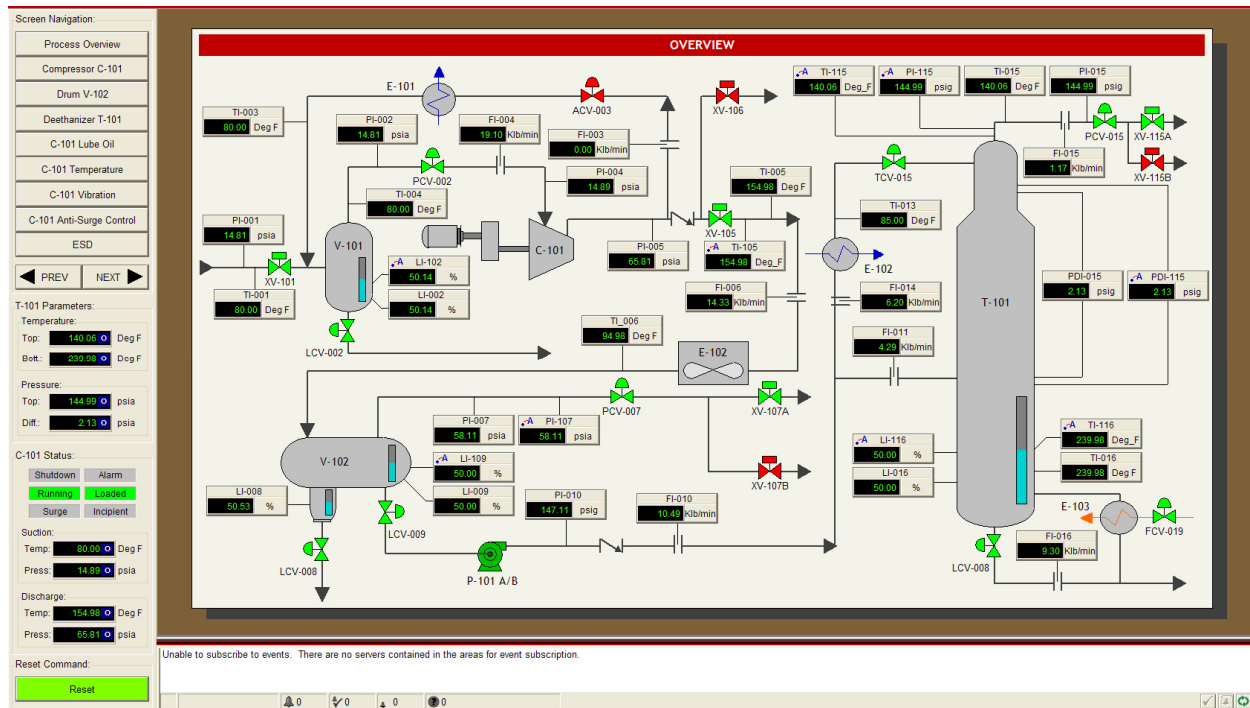


Figure 4: A More Recent, But Still Ineffective HMI

Operator error has been cited as a major factor in many accidents. Many of the errors actually stemmed from poor situation awareness caused by what may be better termed “design-induced error”. It’s not that people make bad decisions or act poorly; they most often simply misunderstand the situation they’re in.

For example, a poor HMI was considered one of many contributors to the 2005 accident in Texas City, TX. The accident involved overfilling a distillation column and a blow down vessel (when no more than 10 feet of liquid was supposed to be present in the distillation column). How could the operator have allowed this to happen? The level transmitter indicated a high level alarm, but the high level switch did not. The switch was not working properly, the transmitter was not calibrated properly, and the transmitter was incapable of measuring a level beyond 10 feet. One screen showed the amount of material going into the column, another showed the amount of material going out. No single screen showed the *information* the operator really needed – the difference between the two – the material balance. Had this useful piece of information been presented – along with the range of values it should be, and that it had been exceeded by orders of magnitude – the conditions leading up to the accident may never have developed. The operator was completely unaware that anything was wrong.

A Medical Equivalent

Imagine that you're going to see your doctor for a checkup. You lie down on a bed, a technician connects various sensors and monitors to you, and the technician then views a display like the one shown in Figure 5.

Just as your plant process is represented as a P&ID with spinning pumps and numbers representing raw data, this medical screen shows a graphic of a body, complete with a pumping heart and lungs that expand and contract. Raw data is displayed. Is this person healthy? What *should* the numbers be? How long does it take you to scan and interpret the information? Are the numbers meaningful to you? How much training and experience would you need to understand this raw data?

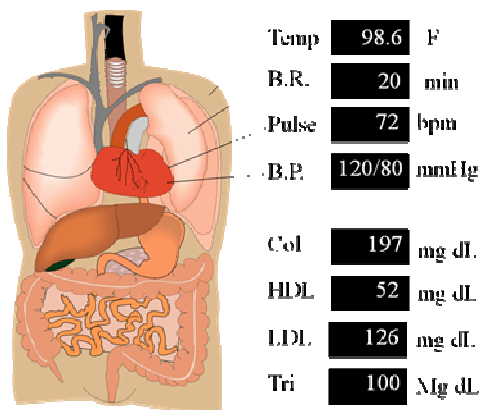


Figure 5: Sample Medical Display #1

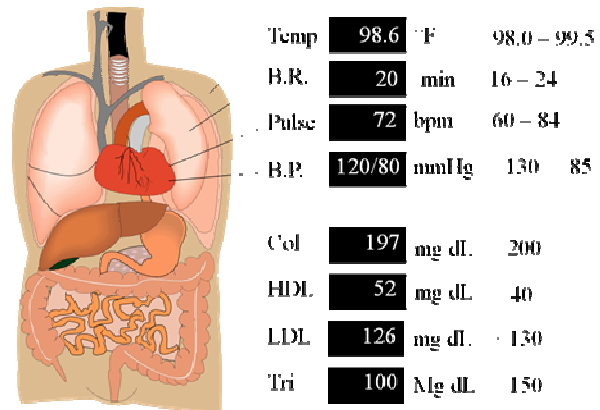


Figure 6: Sample Medical Display #2

It might be easier to interpret the information if you knew what *range* each number should be within. Figure 6 represents a slight improvement, but how long does it take you to scan the information and determine if each number is within the proper range, and by how much? Might there be a better way still of displaying this information?

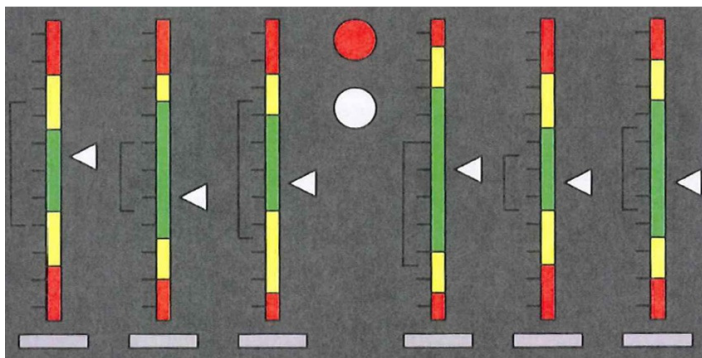


Figure 7: Sample Medical Display #3
(Source: The High Performance HMI Handbook)

Text fields are an inefficient way for humans to interpret information. Humans can interpret more information more quickly if it's represented *graphically*. The actual numerical values don't even matter if they're within normal limits. Figure 7 shows the Star Trek medical display from the mid 1960's. It takes less than two seconds to interpret this display! This is *information* (Level 2 SA) rather than raw data (Level 1 SA) that requires interpretation.

A More Effective HMI Design Process

An enormous amount of data can be made available to operators today. However, the amount of data available can easily exceed an operator's ability to effectively process the information. The following decisions need to be made.

1. Among the vast quantity of data, what is the information that the operator needs?
2. What is the best way to present that information to the operator?
3. How should that information be organized?
4. What information should be emphasized?

An effective interface design process can help answer those questions. The process consists of the following three steps.

1. requirements analysis
2. design
3. measurement and feedback

The **requirements analysis** is the most important phase. There must be an operational concept of how the system will be used. Environmental conditions and user characteristics must be defined. Operational requirements consider how the users work and accomplish their jobs. A goal directed task analysis is used to identify high level goals (not the pre-conceived tasks to accomplish them), decisions, types of cognitive processes users employ, their need for interaction with others, and their SA requirements. This can be determined through interviews and observation. The result is a system requirements document.

Part of the **design** process consists of a function analysis and function allocation. Define what functions need to be done to accomplish the job, such as monitoring of information, generation of options, selection of actions, or the implementation of tasks. Function allocation specifies who will then perform each function, such as the human, the machine, or a combination of both. Information should be displayed based on the operator's goals, not based on the technology providing the data (readouts of temperature and pressure values). Research has shown that when automation aids in or takes over task implementation, overall performance improves. However, when automation is used to generate options, performance declines.

Displays should provide Level 2 SA information that supports comprehension, rather than Level 1 data that requires cognitive effort. For example, display a level deviation directly rather than require the operator to mentally calculate the difference between the direct reading and the desired value. Provide assistance for Level 3 SA projection of future status through the use of trend displays. The operator can then see where the process is heading. The operator can then be proactive and recognize impending problems, rather than being reactive and responding to alarms and problems after the fact. Think of ways to keep the operator active and in-the-loop, rather than as a passive observer. For example, if you were to ride as a passenger to a new and distant location, how comfortable would you be navigating your way back if you had to drive yourself? Passive processing leads to poor situation awareness.

In terms of **measurement and feedback**, early prototypes allow input from both users and designers so that the iterative process of design convergence can occur. An evaluation of user workload and SA can be done, although objective measures can be difficult to obtain. Situation awareness is an internalized mental construct and creating measures to access and describe it are difficult. Events can be incorporated in the simulation and the individual's response (or non-response) analyzed. Unfortunately, there is not always a direct relationship between good SA and good performance. Operators and/or observers can be asked to rate the quality of SA, although

such subjective measures also have shortcomings. Simulations can be halted at random intervals and operators can be asked a variety of relevant questions to determine their SA.

One example of an effective screen is shown in Figure 8.

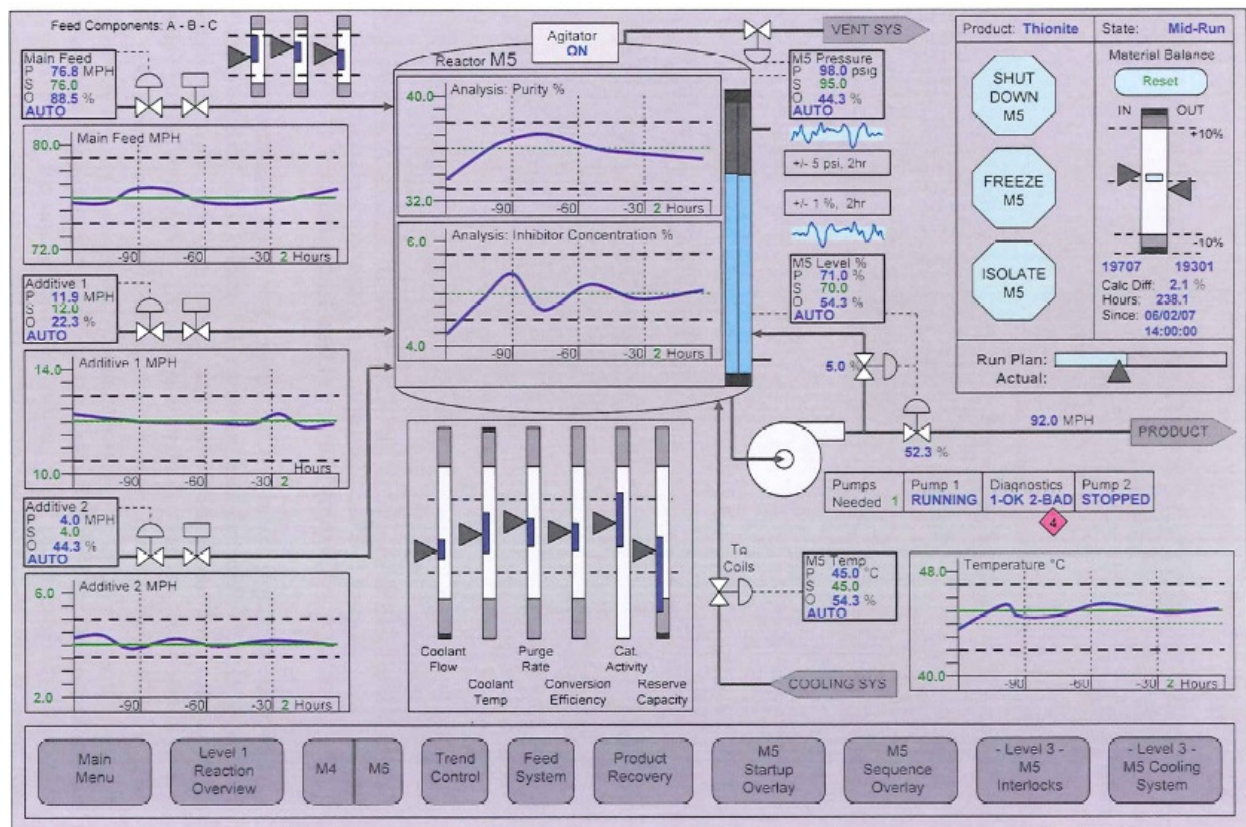


Figure 8: An Effective “High Performance” HMI (Source: The High Performance HMI Handbook)

Just as a Doctor does not need to see a graphic of the human body in order to understand the health of a patient (Figures 5-7), an operator does not need to see a graphic of a plant P&ID in order to understand the health of the process he’s trying to control (no matter what he may be used to or may want). Figure 8 represents Level 2 and 3 SA information. Analog bar indicators show the current status of the process better than displaying raw data and taxing the operator to interpret it all. Trend graphs show both the current and projected performance of the process. The operator can now actively take corrective action before the process approaches or exceeds normal limits. Displays are low contrast gray with very limited use of color. Colors such as yellow and red should be used in limited amounts and for alarming only. Whether a pump is on or off, or whether a valve is open or closed, should not be called out to the operator, unless the item is in a state that it should not be. Clicking on buttons or other areas of the display can take the operator to more detailed screens. The number of mouse clicks to get to any particular information should be limited.

Characteristics of Poor HMIs

- P&ID representation
- Presentation of raw data as numbers (temperatures, pressures, etc.)
- No trends
- Flashing/spinning graphics
- Bright colors, 3-D shadows
- Color coding of piping and vessel contents
- Measurement units in large, bright text
- Lots of crossing lines
- Alarm related colors for non-alarm related elements
- Inconsistent colors

Characteristics of Effective HMIs

- Depiction of process status and values as information, not numbers
- Layout consistent with operators model of the process (not a P&ID)
- Key Performance Indicators as trends
- No gratuitous information
- Gray backgrounds, low contrast
- Very limited use of color (for alarming)
- Consistent visual and color coding
- Gray process lines
- Measurement units in low contrast lettering, if used at all

Conclusions

Douglas Adams said, “Human beings, who are almost unique in having the ability to learn from the experience of others, are also remarkable for their apparent disinclination to do so.” Change is difficult. The suggestions in this paper will not be accepted by many (no matter what the body of research may suggest) and implementing the suggestions will not be easy. In order to do so, there will need to be involvement and buy-in from management, technical staff, and operators. Perhaps the basic education and information presented in this paper will be a useful first step. Further details are provided in the references cited.

Acknowledgments

The author does not claim to be the original developer of the bulk of this work and gratefully acknowledges the authors listed in the reference section.

Author Bio



Paul Gruhn is the Training Manager at ICS Triplex (a Rockwell Company) in Houston, Texas. Paul is an ISA Fellow, a member of the ISA 84 standard committee, the developer and instructor of ISA courses on safety systems, and co-author of the ISA textbook on the subject. He has a B.S. degree in Mechanical Engineering from Illinois Institute of Technology, is a licensed Professional Engineer (PE) in Texas, a Certified Functional Safety Expert (CFSE), and an ISA 84 Expert.

References

1. “Designing for Situation Awareness: An Approach to User-Centered Design” by Mica Endsley, Betty Bolté, and Debra Jones, CRC Press, 2003
2. “The High Performance HMI Handbook: A Comprehensive Guide to Designing, Implementing and Maintaining Effective HMIs for Industrial Plant Operations”, by Bill Hollifield, Dana Oliver, Ian Nimmo, and Eddie Habibi, PAS 2008
3. “Human-Machine Interface Design for Process Control Applications”, Jean-Yves Fiset, ISA, 2009
4. Investigation Report, Refinery Explosion and Fire, Report No. 2005-04-I-TX, March 2007, Chemical Safety Board
5. “The Non-Designer’s Design Book”, Robin Williams, Peachpit Press, 2008

Further Information

1. PAS web site: www.pas.com
2. User Centered Design Services web site: www.mycontrolroom.com
3. Abnormal Situation Management Consortium web site: www.asmconsortium.net