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Flying by the seat of their pants: What can High Frequency Trading learn from aviation?

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ABSTRACT

As we build increasingly large scale systems (and systems of systems), the level of complexity is also rising. We still expect people to intervene when things go wrong, however, and to diagnose and fix the problems. Aviation has a history of developing systems with a very good safety record. Domains such as high frequency trading (HFT), however, have a much more chequered history. We note that there are several parallels that can be drawn between aviation and HFT. We highlight the ironies of automation that apply to HFT, before going on to identify several lessons that have been used to improve safety in aviation and show how they can be applied to increase the resilience of HFT in particular.

Author Keywords

Ironies of automation; human-in-the-loop; high frequency trading; flash crash; socio-technical systems.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

We are building ever larger scale IT based systems (and systems of systems) and these systems now permeate much of society. Many of these systems incorporate levels of complexity that make it difficult for an individual to get a good understanding of how they really work. Recent advances allow the technology to achieve levels of 99.999% reliability. These systems are invariably socio-technical systems, operated by teams of people, and we expect people to intervene and save the day when the technology fails.

This situation has persisted since we started introducing technology into the workplace. It is now 30 years since Bainbridge [2] published her paper "*Ironies of Automation*" which analysed the basic irony that as control systems get

more advanced, the contribution of the human operator seems to become more important. Bainbridge's work predates many significant technological developments—distributed systems, personal computers, the advent of the Internet and so on. We are still not giving the operators the resources to fulfil their role, so the ironies of automation still prevail, and we can still learn from the underlying arguments, which are all founded in psychology [4].

The characteristics of aviation and the process industries

Bainbridge focused her attention on monitoring and control activities in the process industries (chemical production, steel manufacturing and so on), and aviation to illustrate the problems. These domains are characterised by being complex and highly dynamic. Although it may be possible (in some cases, at least) to still manually control the processes involved, automation is almost invariably involved. The automation that is used, however, is not always transparent or predictable, which can give rise to automation surprises [35] where the operator's start to ask questions such as "Why did it do that?" and "What is it doing now?" Indeed, the need to oversee the automation is probably best exemplified by aviation. To achieve the appropriate levels of skill required to fly an aircraft with its vast array of instrument displays, dials, switches and levers in the cockpit, pilots were typically taught that they had to aviate, navigate and communicate. The advent of the glass cockpit, where the functionality of many devices was incorporated into computer systems changed the nature of the job of flying an aircraft such that pilots are now taught to aviate, communicate and *manage systems*.

The changes in technology across complex, dynamic domains changed the role of the operator from one of manual control, to one of monitoring and supervisory control. The net effect is that people have become less directly involved in controlling processes as tasks have been automated.

At the point where automation started to become more widespread, many systems designers regarded the operators as a major source of variation and unpredictability in system performance. Their solution was to automate tasks and essentially remove the human operators from the system. This was in contradiction to the body of evidence showing the importance of the interdependencies between

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people and technology and how these are intrinsic to getting work done [e.g., 11, 13].

In most domains where systems are safety critical there are constraints and bottlenecks on how the system is allowed to perform. In process control, for example, the laws of chemistry and physics constrain how quickly some processes can happen, and in aviation, airports only have a limited number of runways, so a scheduling mechanism is used to maintain an efficient throughput of aircraft. The systems have checks and balances in place to assure safety to a very high level.

From aviation to financial trading

In the 30 years since Bainbridge published her work, technology has become ubiquitous. In some domains, such as financial trading, technology now pervades where it never existed before.

For hundreds of years, financial trading was a largely low-tech human activity, involving buying and selling face-to-face on “open-outcry” trading floors (and originally in London’s coffee shops) using little more technology than a pencil and paper. Then, on October 27th, 1986, the “Big Bang” deregulation of UK financial markets [e.g., 7] ushered in a move from open-outcry to screen based electronic trading on the London Stock Exchange (LSE). For the first time, geographically dispersed traders could now trade *en masse* from separate financial institutions. New, anonymous computer-based trading platforms enabled faster transaction speeds, better price discovery and increased liquidity. The markets flourished and huge profits were made. Trading technology was here to stay.

Although financial trading may seem a far cry from domains like aviation, and industrial process control, there are similarities. In some ways markets can be likened to airspace. In airspace, there are multiple airlines interacting and competing for the best slots to make money, whilst in the financial markets there is intense competition between high frequency traders looking to exploit fleeting arbitrage opportunities to make money. Each aircraft that flies through the airspace is monitored and controlled by human pilots whilst each trading algorithm deployed in electronic markets is also monitored and, to a lesser extent, controlled by human traders. In aviation there are regulations that try to ensure safety and efficiency, whilst still providing an environment in which the airlines can make money; in the markets there are also regulations in place to try to make sure that markets achieve efficiency and resilience, whilst allowing trading companies to make money [19].

In the past three years there have been several highly visible failures in financial trading. In the next section we detail one particular type of trading, high frequency trading (HFT), focusing on three significant failures in financial trading, to indicate the types of problems and the issues involved in HFT. We then describe the results that came out of the UK Foresight project which examined the future of

automated trading in financial markets. This is followed by a consideration of more human factors related issues, describing the ironies of automation as they apply to financial trading. After looking at the lessons that HFT can learn from aviation, we conclude by re-emphasising the need to consider financial trading in the markets as a socio-technical system, learning lessons from other domains where similar problems have already been resolved.

HIGH FREQUENCY TRADING

In traditional financial markets, the success of a trader depended on their making timely decisions. These were based on their knowledge of market fundamentals and dynamics, and knowing when to continue to hold a particular position and when to get out. There is invariably a lot of information flowing in the markets, so it has always been difficult for a lone individual to successfully monitor and anticipate events, rather than just react to them as they happen.

After 1986’s Big Bang, further deregulation and technological innovation combined to radically change the landscape of financial trading beyond all recognition. Accelerated by the EU’s 2007 Markets in Financial Instruments Directive (MiFID)¹, there has been a proliferation of Alternative Trading Systems (ATs), including Multilateral Trading Facilities (MTFs) and Electronic Communication Networks (ECNs), enabling trading to take place away from the traditional exchanges. This has produced market fragmentation.

The introduction of technology made it possible to monitor larger amounts of information more quickly than people can, and provided the foundation for algorithmic and automated trading systems. These systems use software to automate some (and sometimes all) of the trading process. They were developed to assist and, in many cases, replace human traders. These systems allow decisions about buying and selling to be made more quickly (and automatically) to exploit fluctuations in markets and individual prices.

At the extreme end of automated trading lie HFT systems that habitually trade relatively small quantities of stocks and shares, often only holding positions for a fraction of a second. If the system can generate a net profit of a few pennies in that time, this can quickly lead to a steady stream of income by carrying out a large number of similar trades.

HFT systems are designed to exploit fleeting arbitrage opportunities that arise between market venues. Their main strategy depends on speed of execution: if another trader manages to execute first, an opportunity will often be lost. This competition has produced a race to zero [19] among HFTs as they try to minimise latency at all costs.

¹ MiFID was proposed to offer new opportunities and innovation, but few anticipated how dramatically it would alter the landscape.

Consequently, HFTs utilise relatively simple/naïve strategies, because they cannot afford the time required to perform a series of complex calculations before they act.

In order to minimise the time it takes to execute, automatic trading systems are normally situated on servers that are physically located as close as possible to the digital stock exchange.

The majority of financial trading is now automated. It has been estimated that in the US markets HFT could yield an annual income of at least of the order of \$10bn [23], although this is currently quite small compared to the overall trading volume (which was about \$50 trillion in 2008).

Whilst the human traders have not completely disappeared, they may now be based in offices situated across the globe. The role of the human trader, however, has been reduced in the same way as has happened in process control and aviation where the operators and pilots are now less directly involved in performing control actions. Nowadays traders are mainly concerned with setting trading strategies and monitoring their execution. Even in the relatively rare situations where the humans are still making decisions, the trades are still executed algorithmically. It is a fiercely competitive world, however, and in the time it takes a trade to execute, there is a risk that another algorithm may have identified that the trade is happening and intervene before the trade completes to make its own profit.

The naivety of HFTs combined with their immensely fast trading times can have profound effects. Here we describe three events to illustrate the deleterious dynamics that HFT can cause in the financial markets. These examples vary in scale of interaction between HFT firms: from the micro-level behaviour of an individual firm (Knight Capital's "technology breakdown"); the mid-level interaction between HFTs in an individual stock (stock price "fractures"); and the macro-level multi-instrument, market-wide interactions (the "flash crash"). It is interesting to note that all of the events we describe bear the elements of the aviation automation surprises we described earlier.

Knight Capital's "Technology Breakdown"

The Knight Capital Group is an American global financial services firm engaging in market making,² electronic execution, and institutional sales and trading. In 2011, Knight ranked number 1 in secondary trading of US equities by share volume among all securities firms; and in

the first three quarters of 2012 Knight's US Equity Market Making traded an average of 128,000 shares per second.³

On 1st August 2012, Knight Capital started live trading using their new Retail Liquidity Provider (RLP) market making software on the NYSE. Immediately they started losing millions of dollars a minute. It was forty-five minutes before the software was stopped, by which point Knight had lost a total of \$440 million [20]. The following day Knight's own share price plummeted on the news, erasing 75% of Knight's equity value. Within six months, a rescue deal was put together by a group of Wall Street firms to prevent Knight having to file for bankruptcy. The downfall of this highly successful HFT firm was entirely due to one disastrous autonomous technology breakdown.

While doubt remains as to the exact cause of Knight's trading loss, Nanex Research's [28] analysis offers the most compelling insight. By forensically analyzing millisecond trade data on the New York Stock Exchange (NYSE), Nanex Research demonstrated that there was a frenetic period where almost all trades alternated between buying at the offer (the lowest price offered by a seller) and then immediately selling at the bid (the highest price offered by a buyer), each time losing the difference in the bid-ask spread. "In the case of EXC [Excelon Corporation], that means losing about 15 cents on every pair of trades. Do that 40 times a second, 2400 times a minute, and you now have a system that's very efficient at burning money" [28]. It appears that Knight had inadvertently deployed their test software as well as RLP!

The test software was designed to fire patterns of buy and sell orders at RLP inside a development platform, but was now doing just that on the live exchange using real money. Neither the traders at Knight, nor the RLP had any idea that anything was wrong because the test software was not designed to feedback any information about profit and loss. The two separate units of Knight software were both buying and selling without any idea of what the other was doing [28].

Alternative explanations for Knight's trading loss include the suggestion that the trading malfunction involved Knight Capital buying \$5 billion of stock in a trade that was intended to take place over five weeks but was actually executed in just 20 minutes [12]. Whatever the ultimate actual cause of Knight's loss, one thing is certain: in the time it took for the HFT system's error to be spotted and the algorithm pulled, it was already far too late for the firm to recover from the devastating consequences.

Stock Price "Fractures"

In February 2012, Johnson et al. [22] published a working paper that immediately received widespread media attention, including coverage in eFinancial-News [33], New

² Market makers provide liquidity to a market by issuing simultaneous quotes to buy and sell a financial instrument or commodity, with the hope of making a profit on the bid-ask spread: the difference between the buy and sell price.

³ <http://www.knight.com/ourfirm/liquidity.asp>

Scientist [17] and Wired [24]. Having analysed millisecond-by-millisecond stock-price movements between 2006 and 2011, Johnson et al. argued that there was evidence for a phase transition in the behaviour of financial markets at the sub-second time-scale. At the point of this transition, the market dynamics switch from a domain involving interactions among a mix of human traders and robot automated algorithmic trading systems, to a domain newly-identified by Johnson et al. in which the automated trading systems interact only among themselves, with no human traders involved. This abrupt system-wide transition from mixed human-algorithm phase to a new all-algorithm phase has been named the “robot phase transition” [5].

At sub-second timescales, below the robot transition, the robot-only market exhibits “fractures”—ultra-fast swings in price—that are undesirable, little understood, and intriguingly appear to be linked to longer-term instability of the market as a whole. In particular, Johnson et al. [22] showed that the cumulative number of fractures observed across the entire market increased sharply during the period that the S&P500 fell most rapidly. Subsequently, as the index began to recover, fewer fractures were observed. This discovery has the potential for significant impact in the global financial markets. If the short-term micro-effects can indeed give some indication of longer-term macro-scale behaviour then it is possible that new methods for monitoring the stability of markets could be developed, offering early-warning systems for future flash-crashes. We return to this point in the discussion on *ex post* circuit breakers in the discussion of the findings of the Foresight report.

In March 2012, a series of laboratory-style experiments where human traders interacted with algorithmic trading agents (i.e., *robots*) in a minimal experimental model of an electronic financial exchange were conducted [5]. The aim was to see if correlates of the two regimes suggested by Johnson et al. occur in such laboratory conditions. Results indicated that when trading robots act on a super-human timescale of 100ms,⁴ the market starts to fragment, with statistically fewer human-robot interactions that we would expect from a fully mixed market. In contrast, when robotic trader agents are slowed to a thinking-and-reaction speed similar to that of humans (of the order of hundreds of milliseconds, up to 10000ms), less fragmentation is observed. Cartlidge and Cliff [5] conclude that this is the first evidence for the robot transition occurring in controlled experimental financial market systems. This discovery and methodology opens the way for a principled research program to dynamically study the inter-relationships between the low level behaviour of automated trading

⁴ The fastest robots were set to “wake” 100ms after a new market stimulus. This is quicker than a human is able to respond to a simple signal.

systems and the global impact they have on market stability. Interestingly, an inadvertently introduced “spread jumping” bug that caused the robot agents to trade at prices far from equilibrium was introduced in the initial round of experiments. Despite the relative simplicity of the market, the bug (which had interesting parallels with the Knight Capital bug) was not spotted in real-time and was only discovered through extensive post-experimental analysis [5].

The “Flash Crash”

The Flash Crash happened in the USA on May 6th, 2010. The US’s Dow Jones Industrial Average Index (aka “the Dow”) was down by over 300 points on the day, but then fell a further 600 points between in the five minutes between 14:42 and 14:47, effectively wiping \$1 trillion from the value of the market. In the subsequent 20-minute period, the Dow recovered most of the 600-point fall. The Flash Crash was the largest within day fall on the index but, perhaps more importantly, it was the unprecedented speed at which the crash occurred that was truly stunning.

That crashes occur in financial markets is self-evident. However, the nature of crashes, in particular the *speed* of crashes, has changed over time as technology has been introduced. For instance, in 1929, the well-documented Wall Street Crash was the tipping point that plunged the Western world into economic depression [16]. On “Black Thursday”, Oct 24th 1929, decades before the invention of the digital computer, the Dow opened at 305.85. By Nov 13th, it had fallen to 199; a 35% decrease in market value in just 3 weeks. Five decades later, on Oct 19th 1987, when electronic trading systems and computer-generated trading were still in their infancy, “Black Monday” saw the largest one-day decline in the Dow’s history (22%). The Flash Crash of May 6th 2010, in comparison, saw the Dow plummet 9% and then largely recover in the space of just 20 minutes. Clearly, as technology pervades, and markets become more dynamic, market crashes can occur at ever-greater speeds.

It was not just the speed of the flash crash that raised concern. This was a new *kind* of crash that had dynamics previously unseen. For instance, within the space of 14 seconds, more than 27,000 E-Mini S&P futures contracts were bought and sold; yet the aggregate net purchases was a mere 200. Ultra-fast algorithms had simply been passing contracts back and forth between themselves at lightning speed in what was described as a hot potato effect.

Contemporaneous with the Dow’s Flash Crash, individual stock prices behaved extremely erratically. Some stocks, like Accenture, plummeted to just 1 cent, while others, such as Sotheby’s, traded at \$100,000. At this value, Sotheby’s had a net worth greater than the entire Chinese GDP! To compensate, the NYSE retrospectively cancelled all trades executed between 14:40-15:00 that were more than 60% away from last print at 14:40. This arbitrary cut-off point

resulted in lots of arbitrary winners but, more importantly, lots of arbitrary losers. Trade dynamics such as these and the resulting ad-hoc interventions severely damaged investor confidence. Traders are much less likely to invest in a company's stock if they cannot be sure whether the share price in 10 minutes will be 1 cent or \$100,000; or if the exchange is likely to cancel trades after the deal has been made.

Furthermore, the Flash Crash has turned out to be a far from isolated incident. Since the Flash Crash, there have been repeated mini-flash crashes all over the world, such as the commodities crash of May 5th, 2011, where Brent Crude Oil suffered a record intraday 13% drop, Copper slid 5%, and Cotton fell 8% [34].

After 2010's Flash Crash, it took the US Securities and Exchange Commission (SEC) and Commodity Futures Trading Commission (CFTC) almost five months to publish its official report [6]. They attributed the event to Waddell & Reed's large mutual fund selling an extraordinarily large number (75,000) of E-mini S&P contracts which exhausted the number of available buyers. This was followed by HFTs aggressively selling, thereby exacerbating the effects of the large sale, and contributing to the sharp fall in prices. In other words, the CFTC/SEC blamed a combination of fat fingers (a trader hitting the wrong button) and HFTs.

The CFTC/SEC report has been widely condemned for its explanation of events. Nanex [29], for example, conclusively showed using millisecond tick data that the Waddell & Reed algorithm "*was very well behaved; it was careful not to impact the market by selling at the bid, for example*". In simple terms, this means that the Waddell & Reed algorithm waited for buyers to accept its selling price each time it sold, rather than (as the CFTC/SEC suggested) aggressively dumping stock into the market at any price it could take. The mutual fund's algorithm will have had some influence on the market, however, as it was targeting volume in its strategy [36]. Also, the claim that somebody inadvertently sold more stock in Proctor & Gamble than intended has been refuted, and the role of HFTs remains a matter of contention. Several alternative explanations for the Flash Crash have been advanced. Some are still the subject of debate, such as whether Waddell & Reed's massive sale of 75,000 E-mini S&P contracts led to a major dislocation in the futures market too.

What is clear, however, is that prices only stabilised when the Chicago Mercantile Exchange's Stop Logic Functionality was triggered to prevent a cascade of further falls in the price of E-mini S&P contracts. This injected a five second pause in trading, which was accompanied by a reduction in market pressures. A short time later, the price of the E-mini contracts began to recover, along with the Dow.

In the USA, trading curbs, known as circuit breakers, were subsequently introduced. These are designed to halt trading

in any S&P 500 stock that fluctuates up or down by more than 10% within a five minute period. On the day of the Flash Crash, the process for breaking a trade was not clear to those traders in the market, and trades were only being halted when they were over 60% away from the reference price.

These new circuit breakers, which halt trade to provide a five-minute cooling off period, were initially only introduced for the S&P 500 stocks listed on the NYSE. They have subsequently been extended to other areas of the market, using trigger levels appropriate to that market. Although the circuit breakers may prevent re-occurrence of an identical Flash Crash, they do not eliminate the risk of other sorts of crashes, such as a Splash Crash, where a stock market event splashes out into the currency markets and beyond. This could happen because of the intricate interconnections between trades across markets as people try to keep their trading portfolio risk neutral by balancing it across sectors, markets, asset classes and so on [18].

FORESIGHT ANALYSIS OF THE FUTURE OF COMPUTER TRADING IN FINANCIAL MARKETS

A proposal to establish a project to look at the future of computer based trading in global financial markets was made in early 2010, before the Flash Crash (Cliff, personal communication). The UK Government Office for Science's subsequently commissioned an international Foresight Project on *The Future of Computer Trading in Financial Markets* to look at two major challenges. The first was to explore the effects of the pace of technological change which, coupled to the continual rise in complexity of financial trading and markets makes it problematic to understand the role of HFT (and automated trading in general) on financial markets. The second was to create good evidence and sound analysis of the issues as a basis for informing the development of new regulations for the market.

After two years of extensive examination of evidence from over 20 countries, the final report was published in October 2012 [15]. The report explores how computer generated trading in financial markets will evolve over the next 10 years, using independent academic analysis of the evidence on the actual and potential effects of computer-based trading on financial markets.

Computer trading has transformed the way financial markets operate. Today, over one-third of UK based equity trading is HFT. In the US it may be as high as 60% or more. HFT has been implicated by some as a contributory factor in the Flash Crash, and in other failures as noted above.

The Foresight project found evidence that computer based trading and HFT has had several beneficial effects on financial markets. Firstly, there has been a positive contribution to liquidity, as measured by bid-ask spreads: the difference between the lowest price a trader is willing to sell and the highest price a trader is willing to buy.

Secondly, due to increased market venue competition and greater liquidity, transaction costs for both retail and institutional investors have reduced. Finally, there is no direct evidence that computer based trading and HFT has increased volatility or market abuse.

In specific circumstances such as the Flash Crash, however, it was noted that HFT can have negative effects on the markets. In periods of uncertainty the need for liquidity, which is one of the roles of the market makers, can be critical. HFT market makers, however, tend to leave the market, leading to a disappearance of liquidity, making the situation even more uncertain [36]. Furthermore, self-reinforcing feedback loops can amplify risks and lead to financial instability. The Foresight report proposes that mechanisms for managing and modifying potential adverse effects of computer based trading and HFT should be assessed and introduced. The mechanisms with the strongest supporting evidence and weakest opposing evidence include: (i) the introduction of coordinated circuit breakers; (ii) a coordination of tick sizes across venues; and (iii) market wide standards including coordinated, synchronized and accurate timestamps across multiple trading venues.

Co-ordinated Circuit Breakers

Circuit breakers are designed to temporarily halt trading, thus attempting to restore order in the market by dampening feedback loops to reduce further adverse movement. The breakers can be implemented in two ways: *ex post* and *ex ante*. *Ex post* circuit breakers trigger when a share price has fluctuated above or below a predefined safe threshold. These mechanisms monitor simple price data and activate only *after* the share price has moved out of bounds.

In contrast, *ex ante* circuit breakers are designed to halt trading *before* things go bad. These preventative measures use metrics other than price to monitor the market for precursory indications that instability is more likely to occur. Such circuit breakers can then warn regulators, venues and participants in advance to take appropriate action. One such metric is Easley et al.'s [10] Volume-synchronised Probability of Informed trading (VPIN™) flow toxicity metric. VPIN provides an estimate of the probability of informed trading based on volume imbalance and trade intensity. The value of VPIN was extremely high (suggesting low liquidity) in the run up to the Flash Crash. Easley et al. suggest that VPIN could be used: (i) as an *ex ante* indicator to warn about impending volatility/crashes; and (ii) as a tradable index (like the Chicago Board Options Exchange Market Volatility Index, VIX™) to enable HFT firms (liquidity providers) to hedge their risk as VPIN accumulates before a crash.

Irrespective of whether circuit breakers are *ex ante* or *ex post*, it is critical that they are harmonized across trading venues. If they are not, traders could simply switch to another trading venue when one venue gets halted.

Co-ordinated Tick Sizes

The tick size is the smallest price increment allowable at a trading venue. For instance, if the tick size is 10 cents and the current best bid (highest offer to buy) is €4.50, then the minimum price a buy order can have to post a new best bid is €4.60. Hence, the smaller the tick size, the easier it is (the more opportunities there are) to narrow the spread; i.e., to place a new buy order that is higher than the current best bid or a sell order that is lower than the current best ask. Smaller tick sizes offer more trading flexibility and are thus very attractive to HFT. For this reason, competition between trading venues to encourage HFT participation has led to an arms race between venues offering ever-smaller tick sizes.

Identifying the right tick size involves making a trade-off between two opposing forces, however. On the one hand, a coarser grained tick size offers more incentive for investors to place limit orders—orders to buy and sell at a limit price, i.e., buy at the limit price or lower, or sell at the limit price or higher—thereby boosting the liquidity displayed in a limit order book [1]. The coarser tick leads to a wider minimum bid-ask spread. This makes market making more attractive by increasing its profitability, which should increase liquidity as the number of market makers rises. On the other hand, higher minimum bid-ask spreads raise investors' transactions costs, which leads to reduced trading and a corresponding reduction in liquidity.

As with circuit breakers, the Foresight report suggests that there should be a policy to harmonize the tick size across venues. If they are not, traders could simply switch venues with smaller tick sizes to reduce costs.

Co-ordinated Market-Wide Standards

The Foresight report makes the case for market-wide standards. These include the need for coordinated, synchronized and accurate timestamps across multiple trading venues.

In addition the report notes the need for accurate, reliable data in order to better understand the effects of computer based and HFT and hopefully also prevent further adverse events. It therefore calls for the introduction of a European financial datacenter. This would be responsible for receiving, warehousing and repurposing financial data across all primary European markets.

THE IRONIES OF AUTOMATION IN FINANCIAL TRADING

As in other domains, automation has changed the role of the human (traders), leaving them with two main types of task. The first is to configure algorithms, monitor trades and evaluate results. The real problem here is that it typically takes a human about 150-200ms to respond to a simple stimulus such as a sound or a light. Given that the lower limit for trade execution times is currently around 10µs [19], this means that the system could have made tens of thousands more trades before the trader can respond.

The traders' skills for controlling how trades take place are likely to be out of date as a combination of erosion through lack of practice and changes in the nature of trading across several exchanges. Given that the trading systems are most likely to fail in unexpected situations, the traders may have to perform specialised, rarely (and possibly never before) used actions to regain control. In other words, the operators require *more* skill and need time and resources in order to work out what to do, possibly from first principles.

The second type of task is diagnosing problems with the systems, and determining how to fix them. This is particularly important, given that other systems will attempt to exploit these problems to generate a profit. Diagnosing and fixing the problems requires a combination of cognitive skills, which Bainbridge [2] categorised as long term knowledge and working storage. As long as the traders have a detailed, up to date understanding of the systems they are controlling they may be able to develop novel strategies to deal with new situations as they arise. The context in which the traders make decisions will be encapsulated in a mental model [26], which is updated as the situation changes. Since the traders are usually no longer involved in controlling the trades, however, it becomes harder both to develop and maintain their mental models, and the less they use their knowledge, the harder it becomes to retrieve. So any interventions will often be based on a minimal amount of information until they have had the chance to investigate further, to update their mental model, and to consider the available options.

If the traders are reduced to simply monitoring what the systems are doing, this creates another type of problem. For the most part, and under normal market conditions, the system will run smoothly and predictably. When the information the traders are watching is more or less unchanging, however, they are likely to have problems maintaining visual attention for more than 30 minutes. As their visual attention fades, it becomes harder to detect any visual anomalies. Automated alarms may help, but then the issue of who monitors the alarms arises. One of the classic ironies of automation is that the human has to monitor the system to make sure that it is working correctly, when the whole point of introducing the automation was because it was believed that it would do a better job than the human. Having the traders monitor the automation introduces two problems.

The first is that the trader will require specialised knowledge—acquired through either training, or dedicated displays—in order to be able to monitor the system effectively. The second is that the systems are processing more information at a faster rate than the traders can in order to make decisions. It therefore becomes impossible for the trader to adequately track the system's behaviour in real time. Instead, they will only be able to check the system at a higher level of abstraction and at a potentially considerable time lag.

LESSONS FOR HFT FROM AVIATION

The ironies of automation in financial trading can be overcome, but the solutions—like those for other domains such as aviation—are, as Bainbridge [2] acknowledged, highly dependent on factors such as the size, complexity and speed of the system. We believe that HFT, where the solutions are dependent on the trader's skills and abilities, can learn something from aviation, in particular. Somewhat ironically, several of the solutions are technology based. We fully accept, however, that HFT should not just blindly follow aviation and that great care is needed in finding appropriate lessons and applying them. We are aware of the shortcomings of following checklists, for example, which can make a bad situation worse, as happened in the Swissair Flight 111 air accident [9]. Like aviation, HFT is really a system of systems, so there are potentially lessons to be learned at several levels. Below we highlight some of the lessons we have identified so far.

Lessons from systems of systems

In aviation the way that problems are dealt with requires decision making on several levels. The technology may decide that a faulty piece of equipment should be shut down, or the decision could be made by the pilots. The decision to allow an aircraft that has declared an emergency to land out of turn at an airport requires much more manual co-ordination and intervention between the flight crew and air traffic control. In HFT the decision to shut down a single system down after a failure could be taken automatically, but the decision to shut down one or more trading venues, or even close the markets should require some degree of manual control and co-ordination between traders, regulators and those operating the exchanges. Indeed, the SEC has recently called for the introduction of kill switches, which may reside at the exchanges, to instantly disable an errant trading system [8].

One of the reasons that air transport works on a global basis is because of bottlenecks in the system. Aircraft regularly fly through the airspace of many countries en route from one airport to another without incident. They have to safely end up at airports, however, and how they do so depends on co-operation and co-ordination between pilots, air traffic control, airlines and the regulators, including the independence of ATC from the airlines, and regulations that govern the vertical and horizontal separation of aircraft. Even under free flight conditions, the aircraft still have to form an orderly queue as they approach an airport before they can land. In HFT, however, the traders are the people who oversee how trades progress, and have a vested interest in exploiting any anomalies they may spot. The speed of the trades makes it impossible for the traders to interact with the trading systems in real time. This means that the traders cannot detect a single failure until the effects have become large enough to be noticeable by a human. In the time it takes to diagnose and repair the failure, however, many more trades may have been executed, and possibly have

exploited that failure. Haldane [19] suggests the possibility of imposing minimum resting periods on all trades, which would place a lower level time limit on each trade, and would reintroduce an element of collaboration and communication into the trading process. He argues that this would help restore the balance between market efficiency and market stability; to date regulatory changes have tended to favour market efficiency.

Lessons from systems monitoring

Part of the burden for handling some aspects of aviation safety and efficiency has been passed to the automation. The detection of other air traffic in the aircraft's vicinity, for example, is nowadays handled by the aircraft's Traffic Collision Avoidance System which automatically generates alarms on several levels. If technology is to provide at least part of the solution within HFT, however, it becomes even more important that any technology failures are immediately obvious to the traders and the markets as a whole. If a system is frequently generating alarms, for example, then the traders will become quite experienced at routinely handling them. This highlights Bainbridge's final irony which is that the best automated systems which rarely require manual intervention require the biggest investment in training to ensure that the people can appropriately respond when things do go wrong.

In air traffic control, the vigilance problem is dealt with by only allowing controllers to spend limited time at their displays overseeing a sector of airspace. Although this idea could be applied to HFT, it would not overcome the fact that the trades are happening at a rate faster than the traders can track. So they could only monitor trading at a higher level of abstraction.

Accident investigation in aviation relies on forensic evidence from the aircraft's cockpit voice, and flight data recorders. These are used to piece together what happened in the aftermath of the accident. Up until very recently the SEC simply did not have access to enough data to be able to forensically examine why crashes were happening in the market. They have now employed technology from one of the HFT firms to address this problem. Up until now, the SEC has relied on the official trading record, referred to as the consolidated tape, which details the prices of all trades made on any of the US's stock exchanges. The sophisticated trading firms do not wait the extra milliseconds for the consolidated tape to be released but instead buy the data directly from the exchanges. This allows them to build their own record before the official record is released, and it is more comprehensive because it includes details of orders that were submitted but never completed. Even with the new stream of information from Tradeworx, however, the SEC will still not have a completely comprehensive picture of the market. For example, it will not have access to data for trades executed in dark pools—trading venues that do not require adherence to the reporting rules used by the public exchanges [32].

Furthermore, the details of who is placing the trades will only become available once the consolidated audit trail is introduced in the next few years.

Lessons from regulation and standards

The need for effective regulations and regulators is critical to aviation. The role of regulators like the Civil Aviation Authority in the UK, for example, includes explicit objectives addressing safety and efficiency. In HFT the role of the regulators like the SEC focuses on protecting investors, but without explicitly mentioning safety issues. Nanex Research [27] recently highlighted that the regulators appeared not to be enforcing Regulation National Market System (NMS) and subsequently suggested that rather than being enforced, it had been rescinded [30]. Regulation NMS covers the issue of the National Best Bid or Offer which is supposed to assure investors that they are getting the best price for any stocks they buy and sell. The emphasis on speed at all costs in automated trading has made it virtually impossible to show a definitive audit trail for whether an investor received the best price. The regulations also exist to prevent quotes being generated to manipulate other traders in the market—so called quote stuffing—but are not being applied. Nanex Research suggests that quotes should have a minimum lifespan of 50ms.

There are recognised standards for developing software for aviation. RTCA/DO-178B (version B) (also known as EUROCAE ED-12B), is the de facto standard used by regulators like the FAA to decide whether software will perform reliably in an airborne environment. This standard, which was published in 1992, provides guidelines for assuring that the software and equipment will perform its intended function with a level of safety that is compliant with airworthiness requirements. In HFT, the overall safety of the market has effectively been ignored, with traders switching from one algorithmic trader to another to exploit anomalies as they arise in the live market regardless of the effect they may have on that market. The SEC has recently called for new regulations on software testing and reliability after the Knight Capital fiasco, including new software standards [31].

In aviation, there is often a long lead time between the conception of a piece of equipment and its being introduced into the industry and made mandatory. Rigorous testing and certification are required before the new equipment is deployed. S-mode datalink, for example, was originally conceived in 1975. It has only been mandatory for aircraft flying under visual flight rules in Europe since 2005, however [3]. In stark contrast, the lifetime of trading algorithms is very short, with traders typically introducing new algorithms every few weeks. A system of governance requiring evidence of testing, or a system of certification would help to regulate the appearance of rogue algorithmic traders in the markets.

Lessons from organisational learning

The aviation industry has generally been very good at managing the effects of the ongoing introduction of automation. Many of the important issues associated with glass cockpits in the mid 1990s were encapsulated by the FAA's Human Factors team's report, *The interfaces between flightcrews and modern flightdeck systems* [14], for example. Flight deck technology has evolved considerably in the intervening period, but the skills needed to deal with the changes in technology have not. At the same time manual skills have been eroded as the pilots rely increasingly on the technology to fly the aircraft, making it harder for pilots to know how to (and be able to) recover from a stall, and carry out a go-around in the event of a missed approach when coming into land. Even though regulations for recurrent training of pilots exist, there have been recent calls for changes to the recurrent training regulations in order to reconcile pilot skills with the newer technologies [25]. Manual control skills, such as being able to recover from a stall, and carrying out a go-around in the event of a missed approach are being eroded. These examples show that the regulators need to self-monitor, and regularly revisit the regulations to learn which ones are still applicable, and whether they are still being appropriately policed and enforced.

In the aftermath of an aviation accident, there is invariably an accident investigation, carried out by an agency that is independent of the regulator. In the UK, for example, the Air Accident Investigation Board (part of the Department for Transport) would produce a report which it would send to the Civil Aviation Authority which regulates aviation and is a public company, rather than a government agency. The accident report produces clear and timely findings, identifying lessons that can be learned, and where changes may be needed to improve safety. In most cases there is general agreement with the findings, and where there is disagreement, it is often a matter of degree. In contrast, the CFTC/SEC report on the Flash Crash was widely condemned for being late and inaccurate. The SEC is now considering the need for external retrospective assessment. It has been noted that "[w]ithout some assessment ... we may never know what went wrong—and we run the risk of trying to prevent the wrong problem" [21].

SUMMARY

On the face of it, high frequency trading and aviation could hardly be more different. Both are striving to achieve resilience—in the markets, and in air transportation respectively—whilst still allowing companies to make a profit. We have, however, identified several underlying similarities in the ways that HFT and aviation work.

Up until the Flash Crash in 2010, HFT emphasised profits over resilience but since then there has been an increased focus on improving resilience. Based on the identified similarities between HFT and aviation we have highlighted several lessons where we believe that HFT can learn from

aviation in the areas of technology, regulation and software development. We regard these lessons as the start of the process of improving resilience in the HFT markets (and potentially, beyond). Our intention is to build up a comprehensive list of lessons that can be used to improve and maintain the resilience in the HFT markets.

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