As the cost of fuel increases and environmental regulations get tougher, it is more important than ever to transport cargo in a fuel-efficient way. There are many ways of doing this, but reducing speed is more straightforward than most. Assuming the cargo is of relatively low value, the cost of shipping can be divided into three approximately equal groups: the cost of fuel, the cost of the ship, and the cost of the crew. While the first cost will decrease due to lower speed, the other two will increase due to the longer shipping durations. So can crew costs be kept at an acceptable level – without reducing safety? SSPA is heavily engaged in finding autonomous navigation solutions to make sea transport safer, cheaper and more environmentally friendly.

Why now?
Decreasing risk while lowering the workload of the crew has been a major issue for the industry for a long time. The reason it is finally possible to do something about it is the same as the reason why we now have self-driving cars on our public roads: the growing power of computers. It is described by Moore’s law, which says that the computational capacity of computers doubles every two years. It has been going on since the 1950s, and it is continuing. Every time it was considered impossible to keep up the pace, engineers have found a clever way of maintaining it, which is perhaps the greatest engineering accomplishment since the Second World War. To understand the power of doubling something at regular intervals, we will first take a leap back in time and place.

It is said that the inventor of the game of chess was asked by the emperor of India what reward he wanted for his invention. The inventor said that he simply wanted one grain of rice on the first square of the board, two on the second, four on the third, and so on. For each square he wanted twice as many grains of rice as on the previous square, until the last square of the board was reached, square number 64. The emperor happily agreed to this reward and thought the peasant very modest. But as the grains of rice were placed on the board, he soon realised that the inventor was not as modest as he was cunning. The sum of all the grains of rice placed on the board will eventually amount to $2^{64} - 1$, or a pile of rice that would be larger than Mount Everest. The tale clearly shows the impact that the power of two can have, if you continuously double a value over time it will eventually grow to be very large.

Over the last decade, this doubling of computational power has changed many industries profoundly, as described in the book “The Second Machine Age” by Brynjolfsson and McAfee, for example. What Moore’s law states is that this will continue and accelerate. It has now been some years since computers started beating humans at chess. Since then, computers have beaten humans at Jeopardy, and they are now used to control cars in traffic, with a better safety record than humans. Could they control a cargo vessel?

How?
For centuries, controlling a ship has been performed by a division of labour in a way that spans different time scales. There has been a helmsman, steering the ship along a course, at all times watching the course of the ship compared to the course he is set to follow. There has been an officer of the watch, responding to any unforeseen event such as a meeting ship. When a difficult situation arises, the officer of the watch will call on a third person, i.e. the captain. The captain is typically responsible for issuing orders as well as approving the planned route, from the departed harbour to the port of call. Thus the control of a ship can be shared between different persons, with different time horizons.

<table>
<thead>
<tr>
<th>Frequency Of Actions</th>
<th>0.1s</th>
<th>10s</th>
<th>10h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Role</td>
<td>Helmsman</td>
<td>Officer</td>
<td>Captain</td>
</tr>
<tr>
<td>Orders</td>
<td>Heading Wheel</td>
<td>Standing orders Route</td>
<td></td>
</tr>
</tbody>
</table>

**Depiction of the chain of command on board a ship. Each level gives order and watches over the level to the left.**
Automation has already made its mark on this division of labour. It has been a number of years since the “autopilot” was invented. A more suitable name would perhaps be “auto-helmsman”, since in most circumstances it is possible for the officer to use an autopilot instead of a helmsman. This has allowed for a sailor that is probably less bored, and an extra hand for deck work. To further improve the capacity of automation, we must look at the next level of command, the deck officer.

**Behaviour-based control**

Imagine a ship where the pilot has just departed and that is now moving along its track through a series of waypoints. The track was laid out back at port, and has been optimised with regard to the weather, in order to save fuel. This optimisation was performed by a deck officer, perhaps with support from a smart algorithm such as the Mona Lisa system. It is now a matter of following the track, observing and watching out for unexpected events, such as a meeting ship, or the track to follow being blocked by a dredging barge. This is typically the work of an officer of the watch.

Soon enough a ship on a collision course appears on the starboard bow, and according to the COLREG our ship has to turn to avoid collision. But we still want to continue along our planned track, and we don’t want to move out of the fairway. These are the types of decisions that have multiple, sometimes conflicting, goals that the officer of the watch must routinely make. How could they possibly be automated?

Professor Arkin from MIT would say that “behaviour-based robotics” is a good way of weighing up different factors when making a decision. Each factor would be represented by a “behaviour”. Thus in the example above, one behaviour would be to follow the planned track at the planned speed. But behaviour might be to adhere to COLREG and to avoid colliding with the approaching ship. A third behaviour might be to avoid running aground. Behaviour-based control combines these three behaviours into one single, coherent behaviour that avoids collision, but continues on track whenever possible. All while avoiding running aground.

So, what is a behaviour? When it comes to ships it is represented as a demand for a certain heading and a certain speed. Each behaviour calculates how well a certain speed and heading match the goal of that behaviour, and it performs this calculation for all possible speeds and headings for the ship. If the ship is on a track heading south-west, the output from the track-keeping behaviour could look like:

A routine manoeuvre normally performed by the officer of the watch can thus be automated. The two behaviours represented here are just examples of things being taken into account. Other behaviours could influence the ship to stay in the fairway, avoid unnecessary course changes, and avoid no-go areas. Furthermore, the behaviour-based control described is just one of several parts of a collision avoidance system; it may be complemented with algorithms with longer time horizons, such as an RRT algorithm. Nevertheless, it is used today, effectively, to avoid collisions. For example, MIT has used it effectively in their open source robotic platform MOOS-IVP, and SSPA is using it to control simulated autonomous ships. Finally, there is another important area whose solutions are not described here: that of sensors and their importance to autonomous ships: human eyes and ears, AIS, GPS, radar, etc.

However, it will not be able to handle all situations. In the same way that an officer watches over the autopilot when it is controlling the ship, this function can also be monitored. If something seems wrong, or if the algorithm decides the situation is too complicated, the captain can be alerted, and manual control can be retaken. Just as an autopilot will sound an alarm when it is unable to keep its course, this algorithm will sound an alarm when it is unable to handle the situation.

**The known and unknown unknowns**

We may talk about “known unknowns” and “unknown unknowns”. A “known unknown” in the previous example would be the presence and location of an unexpected ship. We may expect that these ships will appear, but we don’t know where. Monster waves used to be an example of an “unknown unknown”: the time of occurrence of these waves was “unknown”, but the very existence of waves of these magnitudes were not known until it was too late, or as Rudyard Kipling eloquently wrote:

> “This new ship here, is fitted according to the reported increase of knowledge among mankind. Namely, she is cumbe red, end to end, with bells and trumpets and clocks and wires which, it has been told to me, can call Voices out of the air or the waters to con the ship while her crew sleep. But sleep thou lightly, O Nakhoda! It has not yet been told to me that the Sea has ceased to be the Sea.”
The sea will indeed not cease to be the sea in the foreseeable future, and thus human input into ship control will probably still be needed. But what about Moore’s law concerning the ever increasing power of computers? Maybe chess, again, can guide us. As mentioned before, computers started to beat humans at chess routinely years ago. But what if the human chess player had a computer as an aid? What if the contest was between a computer-human team and a computer team? Well, this type of contest exists. It is known freestyle chess, and in them the human-computer team routinely beats the computer-only team. Even though the sea is the sea and chess is chess, the same strategy can be applied to ship control. A team comprised of a nautical officer and computer software tools will beat a computer – or a human without a computer.

Thus the case of a ship departing all by itself after the pilot has left it and which travels to the port of call to receive a new pilot may not be optimal. An intermediate step might be closer: that of a ship that is controlled by nautical professionals, but from ashore and with the help of advanced algorithms. These professionals can be located in appropriate time zones and work regular hours. A professional can be tasked with controlling a number of ships, where each ship would handle the tasks of helmsman and officer autonomously, but if a more complex situation were to arise, the professionals ashore would take over and handle it with the help of the advanced algorithms on board the ship. The working conditions of the nautical personnel would improve and their levels of fatigue would decrease. In addition, looking at the statistics on accidents occurring today, these factors are important for the safety of all ships.

**Conclusion**

Automation has been used for a long time to control the heading of a ship. It is now possible to extend automation to also control routine collision avoidance manoeuvres while still keeping a human to watch over the manoeuvres, perhaps while improving working conditions by locating the person on shore. This may not only save fuel, and hence the environment, and money: it may also increase the safety of shipping. These are all good reasons for SSPA and others to continue research in this exciting new area.