Self-repairing Cities

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Image courtesy of Ruby Wright

So much of human history has been taken up with inventing and making new stuff, that now we have rather a lot of it: it fills our homes, our offices, our hospitals – which is all fine except that looking after it all has become onerous. Our cars have become more reliable, more economical and more comfortable, but they've also become more complicated – so much so that repairing them requires specialist diagnostic equipment. Similarly, when our phones break, it's beyond most people's ability to repair them. Even manufacturers would rather replace something than repair it. Infrastructure still gets repaired, but this too is becoming increasingly difficult and expensive. So what is the answer? Should we try to call a halt to this increasing complexity of our material world? There are many who advocate this, but I'm not one of them. My research aims do the opposite: to help create materials and engineering systems that are complex enough to sense when they're damaged, and are able to repair themselves. The main drivers of such self-healing technology are economic and environmental, and it promises to yield cities that are more like forests, in that they're self-sustaining eco-systems.

In the twentieth century, materials were invented that can respond to changes in their environment – they're called 'smart materials'. Later, it was realised that smart materials had been around for thousands of years. A good example is the lime mortar that was historically used to cement bricks and stone together to create buildings and bridges. It starts off as a liquid – a mixture of calcium hydroxide, sand and water –

which, through a chemical reaction, transforms into a hard ceramic that binds masonry together. So far, so normal, but what happens next is interesting. If the foundations of a building move over time, or the building experiences an earthquake, cracks open up between the lime mortar and the masonry. This allows a wall, for instance, to shift instead of collapse. Then, over time, the cracks heal up and the new shape of the wall becomes permanent. The autonomous repair comes about as a result of a crystallisation process inside the material that harnesses damp air to react with unreacted lime inside the mortar. What this means in practice is that walls can maintain their integrity through thousands of years in the face of changes in their stress loading.

The idea of engineering new smart materials that react to damage in a similar way to lime mortar has accelerated in the past decade. The aerospace industry has been developing self-healing composites as a way to deal with microscopic cracks that grow in aircraft fuselages. Such self-healing materials not only offer improved safety, but also increase the life-span of the aircraft, and so reduce ownership costs. These technologies work by incorporating microcapsules of liquid resin inside the material and by coating the reinforcing fibres inside the composite with a catalyst. In the event of a crack forming, the microcapsules burst open and liquid resin flows into contact with the fibres; the catalyst then causes the resin to solidify rapidly and so heal the crack. At present, this only works for micro-cracks because the resin capsules are so small. But there have been versions developed in which the liquid resin is continuously pumped through tubes inside a composite material, in much same way that our blood is pumped through our veins. By imitating the clotting mechanism that our bodies employ to heal a wound, these smart composites are able to self-repair.

Mimicking a vascular system is just one way in which the growing sector of self-healing materials takes inspiration from biological organisms. The development of self-healing concrete is another example. It began when scientists started to investigate the types of life forms that can survive extreme conditions. A bacterium called *bacillus pasteurii* was discovered to be able to withstand highly alkaline environments, as high as those found in concrete. The bacterium also has another extraordinary property: it excretes a mineral called calcite, a constituent of concrete. These unusual properties have made the production of self-healing concrete viable through the incorporation of the *bacillus pasteurii* inside the concrete. Under normal conditions, the bacteria lie dormant, and can do this for decades. But if a small crack opens up in a bridge, tunnel or building made from this self-healing concrete, the bacteria are exposed to humid air and so wake up. They look for food and find it in the form of starch capsules left inside the concrete when it was manufactured. They eat the food and excrete calcite. Then they eat their way out of the crack, arriving at the surface to leave pristine material behind them. This self-repairing mechanism has been shown to restore 90% of the concrete’s strength.

Infrastructures are a major application for self-healing materials not just because they’re associated with major repair bills – in the UK alone it’s estimated that the repair and maintenance of structures costs £40 billion a year – but also because during repair, the services provided by such infrastructures become unavailable. This impact is felt particularly by users of rail and road, which are used continuously, and so closing parts of a rail network even on the weekends is very disruptive. Similarly, lane closures of motorways causes disruption, economic impact and pollution due to traffic jams. Wouldn't it be nice if our roads, and indeed all infrastructures, repaired themselves? This is the aim of a major grand challenge project funded by the UK’s Engineering and Physical Sciences Research Council, led by Leeds University, and with the engineers from Southampton, Birmingham, and my institute at UCL all part of a research consortium. The research project also includes Leeds City Council. They’re making the city a test-bed for the new technologies we develop. The reason why the Council is so enthusiastic is that it’s painfully aware of how much of its annual budget goes on repair and maintenance – it runs into tens of millions of pounds. It sees an opportunity to slash this bill drastically by creating city-wide autonomous repair systems that do more than repair roads and bridges and act like a metropolitan immune system.

To see how this can work in a city environment, consider a pothole that develops in one of the city's streets. At the moment, this must be manually identified, reported, added to a list of road repairs that need to be carried out. An assessment of the urgency, the cost of closing the road, and the cost of sending out a truck and a repair crew must be carried out. The outcome of this assessment affects the likelihood of this repair being performed in that financial year. But of course, if not dealt with, the pothole isn't going to heal itself; in fact, it will only to get bigger and more expensive to repair. Now, consider an alternative future where information from a driverless vehicle that continually surveys the city infrastructure identifies the pothole at an early stage. The information of the size and shape of the nascent pothole is relayed to another autonomous vehicle that's deployed at night when traffic flow is low. It locates the pothole, stops for a few minutes using hazard lights, and then uses a 3D printer to deliver tar to exactly repair the hole. By repairing it at an early stage before it has become big, it saves money by preventing the congestion caused by road closure.

But is it possible to 3D print tar accurately into a hole of a defined size? Working out how to do that is our job in the research consortium. We're making good progress on this, but what has already become clear is that we needn't be confined to repairing the roads. Our 3D printing systems fit on a drone, and so using tar to repair flat roofs and other hard-to-access infrastructure is possible too. In fact, repair drones look very promising as a way for complex cities like Leeds to reduce their repair bills. Take, for example, something as seemingly trivial as a roof gutter blocked by falling leaves. After a while, if not addressed, water overflows and pours down the outside of the building, this causes water infiltration, dampness, peeling plaster and internal mould growth. Finally, after several years the situation gets bad enough for the Council to act, but now the cost is a hundred times higher than clearing a gutter. A drone equipped with the ability to clear leaves and repair a leaky drain sounds like an insignificant piece of technology, but its impact on the repair and maintenance bill of cities like Leeds could save them millions. That's why Leeds City Council is in the project: it sees the future of infrastructure repair as being more autonomous.

This all seems a long way from the simple self-healing lime mortar, but in my view, not only is it a possible future, it's the only future we can afford. Cities today are complex assemblies of services delivering electricity, water, gas, transport, food and healthcare. As expectations have increased for higher quality of life, so has the complexity of infrastructure that supports it – in effect, the amount of infrastructure per person has increased. But as material complexity has increased, our ability to manage that complexity, and in particular, to repair interrelated systems has not kept pace. If you compare a city to a living organism, the difference is obvious. In our bodies, most of the repair that goes on is autonomous: our bodies detect damage and employ systems to repair it. Occasionally, of course, we do need radical intervention that requires surgery, but the reason why we live so long is that our bodies are constantly self-repairing. Crucially, our body's repair systems intervene before a problem becomes critical.

Material complexity isn't just a challenge of large engineering systems like cites; it's also manifest in smaller objects such as cars, computers and phones. As the electronics and power requirements have become ever more complex, so it has become expensive to repair a car or a smart phone. This has led to shorter lifespans for these technologies. For instance, smartphones are used on average for eighteen months before being replaced. This business model may be lucrative for manufacturers, but it doesn't make much economic sense for the rest of us. Nor is it good for the environment, since the material complexity makes it more difficult and energy-intensive to recycle. Why can't a phone last for ten years like a car, and why can't a car last for a hundred years like a house? It all comes down to the cost and viability of repairs. A truly 'smart' phone would repair itself, and surely, as with cities, this is the only economically sustainable future.

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