A Proposal for the Development of a Robot-Based Physical Distribution and Transportation Network for Urban Environments

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ABSTRACT

The personal automobile ushered in a renaissance in individual freedom of movement. This general-purpose vehicle is capable of fulfilling almost all of the local and regional transportation needs of the average citizen. It can commute the owner to work and leisure, ferry passengers, deliver packages and groceries, and in many cases can even haul other modes of transportation like bicycles, snowmobiles, trailers and boats. However, like any general-purpose system, serious inefficiencies must be tolerated in individual tasks in order to provide such a wide breadth of capabilities. In the computer industry, general purpose processors initially replaced machines engineered for specific tasks, but more recently are being replaced by dedicated, high-performance hardware such as graphics processors. Similarly, the technology associated with transportation, localization and tracking lends itself to the consideration of specialized systems for realizing quantum leaps in efficiency. We therefore propose a novel variant of an automated transportation system: a dedicated network of transportation robots for delivering small-to-medium scale physical objects within the range of commuter automobiles for use by the general public. This system is intended to reduce the inefficiency, energy waste, pollution and congestion associated with transporting a large general-purpose vehicle and a human driver in order to deliver small quantities of physical goods in high density urban areas.

INTRODUCTION

Transportation-related activities are the second largest consumers of energy in the United States and the “largest contributor to the nation’s greenhouse gas emissions of carbon dioxide” (EIA 2005). In addition to the financial cost incurred through energy expenditure and environmental degradation, transportation in urban areas is responsible for large costs due to reduced productivity of workers who spend unnecessary time engaged in transportation-related activities. The Texas Transportation Institute estimates that individual travelers in 2007 experienced an average annual delay of 36 hours per year, wasted 24 gallons of fuel and lost $757 due to congestion costs. The US as a whole experienced 4.16 billion hours of travel delays, wasted 2.81 billion gallons of fuel, and lost $87.2 billion dollars due to congestion (Schrank et al. 2009).

Numerous trends are exacerbating these problems. Population centers are becoming increasingly urbanized, traffic jams occur more regularly and for a longer duration, and worldwide motor vehicle ownership is increasing in line with other quality of life indicators. As more vehicles attempt to come on the road in increasingly concentrated urban areas, the cost to transport materials in terms of both energy and time resources spirals upwards in a positive feedback loop.

Based on these trends, it is clear that efforts must be directed towards improvements across the spectrum of transportation systems in order to reduce the feedback coefficients of this loop. Even modest reductions in the rate of increase in resource consumption can result in major long-term strengthening of the economy and preservation of energy efficiencies and the environment. However there are also opportunities for disruptive technologies and infrastructure to interrupt and reverse this feedback loop and set in motion trends towards reduced vehicular traffic, energy consumption per unit of material transported, and resulting carbon emissions. The work proposed here represents such a disruptive technology.
PROPOSAL

Intra-city transportation of materials conceals an extraordinary set of inefficiencies, particularly in cases where private passenger vehicles are used for the point-to-point transport of packages like groceries from the supermarket to one's home. Not only is the majority of the gross vehicle weight being transported a function of the vehicle itself and its driver, but the driver's time is exclusively devoted to the transportation task. This is highly inefficient both in terms of energy usage and human productivity. When the resulting congestion and lengthening of the time constants for every other package on the road are factored in as well, the result is clearly a gross misuse of resources. The ideal solution would be to transport only the package itself, without a support vehicle or human operator. This proposal concerns the development of a system to accomplish this vision.

We propose leveraging advances in technology for localization and tracking of physical objects along with theoretical and algorithmic advances in networking and distribution of electronic data to create a packet-switched network for physical objects. Such a network can be implemented at multiple scales, corresponding to the well-understood digital network taxonomy of Wide-Area Network (WAN), Metropolitan Area Network (MAN) and Local Area Network (LAN). The postal service could perhaps be thought of as a rudimentary WAN-scale packet-switched physical network. However, this batch-processed service clearly does not scale to the smaller time scales and point-to-point routing requirements of a city-sized MAN or installation-sized LAN. The system that we propose is designed to effect timely (on the order of minutes or hours, not days) point-to-point delivery of physical materials within a MAN-sized network while incorporating electronic network optimizations such as dynamic routing, congestion avoidance and management, packet prioritization and real-time packet tracking and delivery estimation, without human intervention.

DESCRIPTION

We envision an urban robotic physical packet-switched network that would consist of a series of tunnels or enclosed pathways located underground, in buildings, and between buildings above ground level which would permit automated electric vehicles to travel through a city without the use of the surface road network. Power will be supplied directly to the vehicles from the system either using a contact based system (third rail, pantograph, etc.) or a near-field non-contact based system like the one being developed as part of the KAIST Online Electric Vehicle program (Ahn et al. 2010). Terminals could be located in businesses, private residences, and public places and allow both commercial and personal use. Terminals could also be used to hold low priority packages for delivery at a later time when network and/or energy usage are low and to securely store delivered packages until they can be retrieved by their owners. Thus, this system will be compatible with a smart electricity grid and is well suited to areas which receive their electricity from hydroelectric, wind, and nuclear power sources which have underutilized base load generation during the late night and early morning hours of the day.

PRIOR ART

The history of unmanned urban freight delivery systems goes back more than 150 years to the early pneumatic tube systems that were used to deliver mail in various European cities. Today, pneumatic tube systems, hydraulic tube systems, autonomous tracked vehicles and automated guided vehicles (AGVs) are commonly used for transport of small to mid-sized packages within and between buildings, particularly in airports, banks, hospitals, and warehouses. Proposals for larger robot-based urban freight delivery systems are also common. For example, researchers at Delft University of Technology in the Netherlands have been working on an underground freight transportation system to connect industrial and logistics centers as part of the OLS-ASH project since 1995 (Pielage 2001). Researchers at the Ruhr-University Bochum developed the CargoCap concept for underground pallet-based freight transportation which is intended to prevent the German economy from being negatively impacted by growing traffic congestion (Stein and Schoessler 2003). And the New York State Energy R&D Authority has explored the feasibility of constructing a large pneumatic capsule pipeline to transport municipal solid waste, mail, pallet goods, and shipping containers into, out of, and through the city (NSERDA 2004).

However, these concepts all focus on creating parallel infrastructure to more efficiently transport cargo through urban areas by avoiding the surface traffic congestion caused by personal automobile usage. They do little to reduce that congestion. In 1996, there were roughly 240 million personal vehicles in the US which traveled a total of 2.5 trillion vehicle-miles. In comparison, there were fewer than 11 million commercial freight vehicles which traveled a total of 182 million vehicle-miles (USDOT 1999). This clearly shows that removing commercial freight vehicles from the roads will not substantially reduce congestion in high density urban areas. In addition, commercial freight vehicles are much more efficient in terms of both the energy per ton of cargo transported and the roadway space that they consume than personal automobiles. Thus, they should not be the first target for engineers, designers, and policy makers who wish to improve energy efficiency in our transportation systems. Finally, while quicker cargo delivery times may be a boon to just-in-time manufacturers
and suppliers who wish to improve their operational efficiency, cargo does not experience the same anxiety, frustration and reduced quality of life that citizens do when stuck in traffic. Thus, we believe that a more human-centric approach to the problem is needed.

HUMAN CENTERED APPROACH

The proposed system differs from other existing robotic delivery networks because it is intended for use by the general public. As such, it has the potential to be a disruptive technology that could change the way that we view transportation, change the way that we use public and private transportation, change the way that we shop, reduce congestion and hydrocarbon emissions, create new service industries and markets, and improve access to goods and services by the elderly and the disabled. However, it also introduces new design challenges. Most existing systems are operated by expert users who have received formal training and use the system on a daily basis. However, members of the general public rarely read instruction manuals before attempting to operate new technology. Thus, usability is a clear concern for all aspects of the system that require human interaction. This is particularly important for the computer interface where requests for delivery and payments are made and for the terminals where packages will be loaded and unloaded.

In addition, the public nature of this system introduces additional concerns about safety, security, and accidental and intentional misuse. It is important to keep children and pets from entering the system through household terminals and to prevent animals and natural and man-made hazards from entering households and business from the outside through the system. From the hardware perspective, terminals must be equipped with security systems (password protection, token based recognition, etc.) to prevent accidental and unauthorized access. Airlock and fire door type mechanisms, both within the terminals and the system tunnels, will be needed to prevent uncontrolled access to adjacent parts of the network. And terminals should contain sensors that will prevent packages and vehicles with suspect properties (vibration, excessive temperature, etc.) from being permitted to enter the network.

In addition, features can be included in the software to permit home owners to accept or reject packages based on their characteristics. For example, they could choose to accept only packages from authorized senders, to accept or reject packages on a case-by-case basis, or choose to reject all packages (for example, if they are away on vacation.) Packages without authorization from the receiver will not be authorized for transport and no delivery vehicle will be dispatched.

RISKS

The major risks of this project are not in the academic theory underpinning the concept but in the implementation details.

As with any project that involves the construction of new large scale infrastructure, there are always risks that a particular technical implementation may prove unscaleable or otherwise infeasible. However, recent advances in the underlying technology, coupled with a growing willingness to support energy-related infrastructure projects that would have until recently been considered too expensive, means that the technical risk of this project is low and the probability of success in that respect is high. Instead, the risk generally concerns the political and institutional will to make fundamental changes on an infrastructural level. We have identified the following principal risks:

1. A prevailing assumption exists that a parallel transportation infrastructure can not be retrofitted to existing urban areas because the expense involved in doing so, and the space requirements that would constrain such a project, are insurmountable. However, there are numerous counterexamples of parallel infrastructure retrofitting to nationwide networks (e.g. the Shinkansen [“New Trunk Line”] parallel high-speed rail network in Japan), metropolitan networks (e.g. new public transport systems in Bangkok), and local networks (e.g. the retrofitting of autonomous field robotic cargo transporters in shipping docks in Australia). In addition, new ‘designer’ cities, particularly in developing economies in Asia and the Middle East, are being developed which may make retrofitting unnecessary or significantly easier than it might otherwise be in an established metropolitan area like NewYork City. Thus, we believe that the primary risk here is that we do not perform this fundamental work while we have the opportunity.

2. The technology to enable widespread real-time localization and tracking of huge numbers of transported items across multiple modalities is arguably relatively new and still in a state of flux. It is possible that new technologies on the horizon will quickly supplant the current state of the art in 2-D visual coding and RFID systems, and any infrastructure developed today runs the risk of becoming rapidly obsolete. This is a risk in the embrace of any new technology. But one has only to look at the longevity of the bar code to realize that the efficiency gains realizable from a well-designed system can rapidly outweigh the cost of development, even if the individual technologies are eventually superseded.
3. This project is essentially a component in the struggle for non-renewable energy independence. All independence struggles carry risks: particularly the risk of failure, and the risk that the post-independence environment will be worse than the current state coupled with the high costs of new infrastructure development. However, it would take an extremely costly failure to equal the long-term costs of continuing the unsustainable energy dependence that currently exists.

POTENTIAL FOR PROOF OF CONCEPT

While a physical packet-switched urban transportation system does represent a parallel infrastructure to the surface road network, and would need to include roughly the same number of connections to approach the functionality of private automobiles and commercial vehicles for freight transportation, the physical size of the vehicles and the pathways within the network would be substantially smaller than traditional roadway vehicles to be able to travel within buildings. Thus, it should be relatively easy and inexpensive to construct a full scale LAN prototype on a university campus or in an office park that would allow both inter and intra-building transport. Since a MAN-scale network would essentially link individual LAN networks through a series of hubs, this should provide full technical proof of concept, including identifying unforeseen technical difficulties. In addition, a network of this size would permit long term user testing within an authentic environment which should provide valuable insight into how such a network would be used in daily life.

CONCLUSIONS

This work has introduced a new concept for a robotic physical packet-switched network which is unique in its focus on providing autonomous intra-city freight transportation to the general public. This new paradigm in urban freight transportation has the potential to alleviate the existing problems associated with private automobile usage in high density urban areas with fewer risks and greater potential for full scale proof of concept before requiring a commitment from the local authorities. A human-centered approach which combines expertise from product design, industrial design, engineering design, and operations management will develop a system that features functionality, usability, customization, and security and will ultimately lead to a better quality of life for its users.

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REFERENCES


