AUTOMATION AND CONTROL IN TRAFFIC SYSTEMS

Ernst Dieter Dickmanns
University of the Bundeswehr, Munich, Germany

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Contents

Summary

This article begins with a brief survey of the development of traffic systems following the introduction of engine power for the propulsion of vehicles. In general, initially, people had to control the function of vehicle guidance completely. With the advent of electronic sensors and computing devices over the last century, especially after the Second World War, more and more guidance functions could be taken over by automatic control. This introductory section concludes with a discussion of the different traffic domains, each of which require specific models, methods, and technologies for automation.

General aspects of automation and control of traffic systems are discussed next. The overall mission is divided into a sequence of mission elements requiring special sensing and control application. The problem of optimal control for mission performance is discussed briefly. Unknown perturbations require a superposition of near-optimal, feed-forward control application according to standardized environmental conditions and some feedback components for counteracting unforeseeable disturbances. Because of the large scales in time and space involved in mission performance, several hierarchical layers for the control system result.

High frequencies and poor damping of the eigen-motion components of the vehicle may require automatic stabilization in order to improve controllability of the vehicle for the average human operator or for the higher-level guidance and navigation loops. The task of the (medium frequency) guidance loop is to keep the vehicle on the proper trajectory as required by mission performance. Monitoring progress of the mission and checking the transitions from one mission element to the next is done by a low-frequency navigation loop.

The global infrastructure required for automation of traffic systems is surveyed, and the onboard means needed for automation in the near future are discussed. Because of the great importance of machine vision for flexible automation of traffic systems, this topic is investigated in some detail. Computing power—at a reasonable cost—that could introduce vehicles with a sense of vision into the market will become available in the 2010s. A possible road map for its introduction is given, based on ongoing research. A new quality of traffic automation will be achieved with this development step.

1. Introduction

Initially, almost all traffic systems had to be controlled exclusively by people. Animals—used for carrying loads or pulling carts—had limited capabilities for understanding their environment. They were able to select their route according to the surface state in a local environment, and even find their way home in a well-known environment. Substituting engine power for animals meant that even this partial autonomy in transportation systems was lost. The gain in power level, speed, and endurance compensated for this loss, but all perception and control had now to be done by the human operator.

After the invention of the steam engine, more than two centuries ago, it was James Watt who in 1788 adapted the flywheel—known from windmills and dubbed the “governor”— for regulating their rotational speed. Servo control of ship rudders by hydraulic actuators was another early application of automatic control. Note, however, that in this case it was not the control of the steering angle that was automated, but only the positioning of the huge rudder according to a preselected value by a human operator. In other words it provided a power boost.

The next big step in traffic system development after the use of steam engines in ships and railways was the invention of the internal combustion engine, and its introduction for road vehicles without animal power in 1885 by Karl Benz and Gottlieb Daimler. Soon—in the first half of the twentieth century—these engines were also being used to open up air transportation. Jet engines—developed during and after the Second World War—within a few decades pushed the speed limit for economic transportation into the transonic drag-rise region—around Mach 0.8—where it essentially still stands today.

The use of diesel engines in ships and on the railways pushed steam piston engines aside, although steam turbines are still used for large ships, especially when fueled by nuclear power. On the railways, electrification is gaining predominance in industrially well-developed areas. Even electromagnetically levitated and propelled vehicles are currently being introduced. Some air-cushion vehicles are in operation as amphibian devices (e.g., crossing the English Channel and as military units), and along these lines, trains have been tested, but not yet introduced for practical purposes. All these propulsion devices may have their own automatic controllers; however, these are not of primary interest here, since the subject matter is automation of the guidance task. (Some aspects of them are discussed in *Automotive Control Systems.*)

During and after the Second World War, rockets for space flight without air intake were developed, allowing high-altitude flight with low drag and at hypersonic speeds. In 1957, the famous Sputnik was the first artificial structure to achieve orbital speed and became the first human-made satellite. Up to now, rockets and satellites have not directly contributed to the transportation of goods around the globe; however, satellites are indispensable as part of present traffic systems. They provide the capability of global weather observation and forecasting, global communication links, and position measurements with systems such as the global positioning system (GPS).

Thus, traffic systems are made up of components carrying out transportation tasks on the ground; on and under (submarines) the water (oceans, rivers, lakes, and so on); as well as in the air, using support from “space-based” systems for global reach. Table 1 gives a survey on the most typical domains of traffic systems. Roads are subdivided according to their properties that require different perception capabilities for automation (see the upper right portion of the table). Beside rail systems, cable cars form a special group of transportation system, both for people and for goods.

Type	**Characteristic elements and functions**		**Specific domains**
Ground-based systems	roads		motorways (limited access)
			highways (state roads)
			inner urban road networks
			dirt roads (unsealed, but hardened)
			cross-country (natural surface)
	rails	tracks	electrified
			nonelectrified
		tracks (beams)	magnetic levitation
			air cushion
	cables	seats and cabins	hanging on ropes
		cars	hauled by cables
			sea, ocean

Water-based	surface		rivers
			lakes
	submarine		military
			research, surveillance
Air-based	“fast and far”	fixed wings (larger airports)	global (at present: hopping) => hypersonic flight
			transoceanic, continental (high subsonic)
			regional (low density)
	Short distance	helicopter (small landing site) dirigibles	point to point, even in cities; transport capability in case of poor accessibility from ground
	surveillance and relay stations (long endurance)	observation and communication	regional
			global
Space	navigation		GPS
			Glonass
			(Galileo)

Table 1. Traffic system domains (relevant for specific techniques in automation)

At present, submarine systems do not play an important role in transportation, except for research, surveillance, and military activities. When the harvesting of ore or minerals, as well as fuel resources (e.g., methane) becomes *en vogue*, the picture will change rapidly. In air traffic, three classes of systems requiring different approaches may be distinguished:

1. fixed wing “airplanes” for fast, longer-distance flights, including general aviation;
2. helicopters for short distances with fast point-to-point connection or for transportation of goods to places not easily accessible from the ground (see *Aerospace*); and
3. dirigibles—steerable airships capable of carrying bulky and heavy loads. At present, they are being reconsidered for special transportation

tasks not appropriate for aircraft and helicopters or ground transportation systems.

For longer-term observation and communication tasks, including traffic systems, both unmanned air vehicles (UAV) and satellite systems are being investigated, and are partly in use already. These systems collect actual information on larger areas on the ground for improving traffic flow. Air-based systems do have the advantage of higher resolution and constant coverage of the same local area—up to a few days. Satellites are more suited for global coverage in general; low-flying satellites can see a particular area on the ground only for a few minutes per orbit revolution of about 90 min. Geostationary satellites are about 40 000 km away, with corresponding loss in resolution.

2. General Aspects of Automation and Control of Traffic Systems

Even though traffic systems may be quite diverse—as can be seen from Table 1—there are several principles that automation systems for vehicle guidance have in common. First, traffic is generated from the desire to transport people or goods—including payloads for research or surveillance—from location A to location B. Very often, this should be done in an optimal sense, in some way. Therefore, planning of optimal routes may be the first step for performing a transportation task. Depending on the costs and possible gains or losses involved, this part is performed in extensive studies in air and space transportation. Weather conditions, such as jet streams and strong turbulence, may influence route selection in long-distance flights—hours of flight time and fuel costs may be saved this way. This problem area will be discussed in Section 2.1.

Monitoring atmospheric states at a larger scale and designing flight trajectories according to the actual conditions is also of relevance for the launch and re-entry of spacecraft. Models of the changes with altitude in the state of the atmosphere surrounding the earth depending on season, time of day, and latitude have to be available throughout the prediction period preceding actual flight. Since these models almost never represent the real conditions that will actually be encountered, “nominal” values are used for trajectory design, using full nonlinear models for interaction of the vehicle with its environment.

In order to be able to cope with perturbations and unexpected situations, in addition to the nominal trajectory, the first-order linear perturbation systems—from a Taylor series expansion of the differential equations—along the nominal trajectory are computed and stored. This general approach will be dealt with in the Section 2.2.

In order to achieve simultaneously several aspects of safe and efficient transportation, continuous monitoring and control on different scales of time and space have to be done. The general threefold cascaded loop of stabilization, guidance, and navigation will be dealt with in Section 2.3. For robust and safe traffic systems, self-monitoring of component and subsystem performance is mandatory. This also reduces human–machine interaction, which is usually implied in today’s automation systems. Finally, Section 2.4 briefly discusses some of these problems.

2.1. Planning of Optimal Trajectories

For complex missions—selecting and designing according to some optimality criterion—the sequence of mission elements is often crucial for success. This is, of course, specific to the individual traffic domain on the ground or on the water surface, underwater, in the air, or for space flight. Beside arbitrarily selected time histories for feed-forward control variables—or from previous experience, which are easily implemented—optimal ones may be derived, as is often done in aerospace engineering where performance is of the utmost importance.

Very efficient, numerical optimization methods are available for solving the corresponding boundary-value problems arising from application of the calculus of variation or optimal-control theory. In this case, both control-time histories and the corresponding state trajectories are the results that have to be stored as background knowledge before the start of the mission; they will then be invoked by a proper trigger signal in the real mission. Special bodies of literature are available for the different domains.

For transoceanic flights with ever-changing wind conditions on a large scale, such optimal trajectory calculations are done on a regular scale based on observations of the weather conditions from satellites and from previous flights. In shipping, known water currents are taken into account. For takeoff and landing, special zones requiring noise abatement procedures may influence the trajectories chosen; for supersonic transport, this may affect transcontinental route selection.

Another point in route selection is the safety aspect, in case a malfunction occurs—there should always be at least one safe alternative to the nominally planned route.

2.2. Realization of Trajectories for Transportation

Strictly optimal trajectories very often require much more effort than close to optimal ones. When the payoff function is flat with respect to small changes in control applied, it is often a good strategy to break down the overall optimal trajectory into mission elements that can be realized using standard procedures or relatively simple devices. In ground transportation, a near freeway (or autobahn, motorway, and so on) may be worth making a detour for; driving without crossings and oncoming traffic on well-structured lanes allows for high speeds and less stress, and may even enable—at least in the near future—automatic modes to be used.

In air traffic, takeoff, climb to the flight level intended, and descent over densely populated areas are clearly separated from cruise; final approach and flare till touchdown again require a different infrastructure for safe performance under adverse environmental conditions. Similar decompositions exist for almost all traffic domains, for example, ships in harbor, passing through tight passages, or on the ocean. From the point of view of automatic control it is important to check which are the most simple and cost-effective means for efficiently realizing such mission elements.

2.2.1. Subdivision into Mission Elements (Navigation)

It is a fact that in almost every traffic domain, navigation in terminal areas is different from navigation in the cruise phase (nonterminal). This fact is valid around the home for road vehicles, in or near a station for trains and cable cars, in a harbor for ships, and around an airport for aircraft.

For the ascent into a geostationary (equatorial) orbit of satellites, several mission elements are again obtained in a natural way. Launch from the ground and ascent through the denser part of the atmosphere are achieved by the boost vehicle, consisting of several stages with their own mission elements, in general. Cruise towards the equator is used for aligning the upper stage of the rocket such that another velocity increment imparted in the equatorial region will bring the payload into a transfer orbit. This is designed to lift the apogee close to the geostationary altitude and to turn the angle of inclination relative to the equatorial plane closer to zero. In transfer orbit, the trajectory actually achieved is determined by extended measurements.

Then the “apogee” rocket is oriented and fired so that it transfers the satellite into a proper, close-to-geosynchronous, “drift orbit,” which will take the satellite towards its planned geostationary position in a certain amount of time. Several small impulses may finally be necessary for fine positioning. These are similar to those needed afterwards for “station keeping” despite perturbations from the sun, the moon, and other sources.

Cruise phases may be interrupted by short maneuvers for selecting a new course—for ships, aircraft, and so on—or for avoiding obstacles (e.g., other vehicles crossing the trajectory). Narrow passages selected as part of the trajectory may also require special maneuvers. Cruise phases may consist of steady control actuation, as in road vehicle guidance along a curved road or boat guidance on a river. In these cases, all connected trajectory parts that can be handled by a certain control law are considered to be one mission element.

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Biographical Sketch

Ernst D. Dickmanns studied Aerospace Engineering at RWTH, Aachen, West Germany (1956–1961) and at Princeton University, NJ, USA (1964/1965). The first half of his professional career (1961–1975) he spent with DFVLR, the German Aerospace Research Establishment, specializing in control engineering for aircraft and space transportation systems, including numerical methods for trajectory optimization. After his Ph.D. in Engineering at RWTH Aachen (1969) he spent a Postdoctorate Research Associateship with the NASA Marshall Space Flight Center (1971/1972) working on re-entry dynamics of spacecraft. In 1974/1975 he was acting head of the Research Center Oberpfaffenhofen near Munich. Since 1975 he has been a full professor of Control Engineering at the Department of Aerospace Technology (LRT), University of the Bundeswehr, Munich. He is the founder of the Institut für Systemdynamik, well known for its activities in the field of dynamic machine vision (4-D approach) and applications to autonomous guidance of both road and air vehicles. In the European Prometheus project (1987–1994) he has been one of the driving forces promoting machine vision for road vehicle applications. In 1996 he was Visiting Professor at Caltech, Pasadena, CA, USA, teaching a course on dynamic vision for autonomous vehicles. In 1998 he taught the same course as Visiting Professor to MIT, Cambridge, MA, USA. He was Guest Researcher at the Australian National University, Canberra in 2001. He has published more than 150 papers both in trajectory optimization and machine vision, and serves as reviewer for six journals and numerous conference program committees.