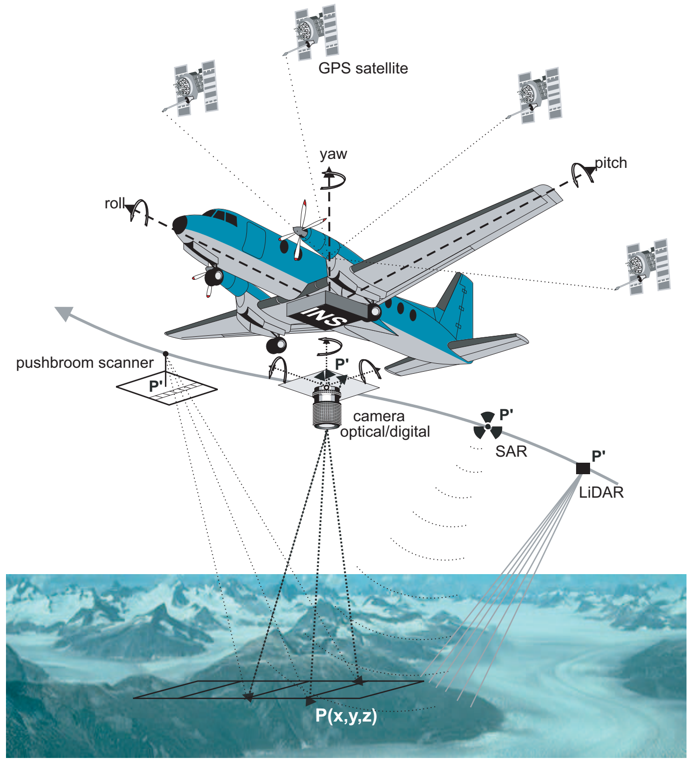

Figure 1.1: Sensor orientation involves the methods and technologies to determine the time varying parameters of a moving object by measurements

The parameterization of the attitude is more complicated. There is no “best” parameterization and its choice is a compromise between uniqueness, redundancy, ambiguity, and visualization possibilities. The popular alternatives are the rotational matrices (9 elements), Euler angles (3 elements), and quaternions (4 elements). Their properties are compared in Tab. 1.1 and will be further treated in Chap. 3.

Table 1.1: Parameterization of attitude

Name	Symbol	Elements	Uniqueness	Singularities	Constraints
Rot. mat.	$\mathbf{R}$	9	yes	none	$\mathbf{R}^T\mathbf{R} = \mathbf{I}$
Euler ang.	r, p, y	3	no	yes	none
Quaternion	$\mathbf{q}$	4	no	none	$\mid \mathbf{q} \mid = 1$

1.3 Systems and techniques

A navigation sensor measures quantities related to one or more elements of the trajectory and thus the navigation state. A combination of sensors capable of determining all (relevant) navigation states make up a navigation system. For instance, the combination of triad of gyroscopes and accelerometers together with a navigation computer make up an inertial navigation system (INS). A sensor that supplies only partial information on the navigation states or that is used as a constraint on some of the states will be called navigation aid or briefly “navaid”.

Technologies that can be used to manufacture sensors allowing for the estimation of the navigation state are called navigation technologies. Certainly, different sensors can be used to determine a navigation state or navigation states, such as the position state or the attitude state. In principal, there are two major concepts in which measurements from different navigation sensors can be combined to obtain the position state:

- Dead reckoning (DR) is the determination of the current vehicle position from the knowledge of the previous position and the measurement of the direction of motion and the distance traveled. It is therefore a relative positioning method and its performance depends on the accuracy of the initial coordinates and the accuracy with which velocity and heading can be determined. An example of a DR system is an inertial navigation system (INS) which derives its position, velocity, and attitude from integrating the sensed accelerations (more precisely, forces) and angular velocities after transformation to a navigation frame. Since all unaided dead-reckoning systems are open loop systems, error accumulation with time is their main limitation.

- Position fixing refers to the determination of the current vehicle position from measurements to known reference points, but without reference to its previous trajectory. It is an absolute positioning method in the sense that the measurements are made with respect to a given reference system which is well defined relative to a global reference system. The measurements are usually via radio frequency (RF) transmission and a typical system of this type is the Global Positioning System (GPS) where the instantaneous position is determined by ranging to a number of satellites (the reference points) whose (time-dependent) positions within a global coordinate system are well known. As indicated by its name, position fixing does not include attitude determination and does therefore not provide the full navigation state.

Table 1.2 shows the implementation of different concepts of kinematic trajectory determination in today’s standalone system.From the properties of the individual systems listed in the table, it is obvious that dead reckoning and position fixing are essentially complementary methods. While position fixes (e.g. as those offered by satellite positioning) are only available at relatively long time intervals, dead reckoning is the primary method. However, all dead-reckoning systems are affected by unfavourable error growth. Intermittent position fixes are therefore very useful in limiting the error growth. If it is sufficient to have accurate position estimates at extended time intervals, position fixing will be the primary method. However, integration with a dead-reckoning system will provide trajectory interpolation between fixes with the possibility to identify and exclude faulty measurements. Systems which combine both methods (e.g., dead reckoning with position fixes as updates) will be called integrated systems.

Table 1.2: Different techniques for trajectory determination

Concept	Observables	A-priori known	Characteristics	Problems	Systems
Inertial positioning (DR)	Specific force Angular rate	Initial position Earth rotation Gravity field	Global Autonomous Acc. degrades	Error growth	INS
Resection from terrestrial points	Ranges (range rates)	Station pos.	Local Dependent Low accuracy	Shading Synch.	Loran-C Cellular pos.
Resection from satellites	Ranges (range rates)	Sat. pos. Earth rotation	Global Dependent	Visibility Vulnerability	GPS GLONASS
Vision-based pos. (DR)	Image coords. of homologous points	Initial position and orient. or control pts.	Local Dependent	Target track. Geometry Error growth	Machine guidance

1.4 Sensors and sensor fusion

A navigation sensor measures quantities related to one or more elements of the trajectory or navigation state. The individual navigation states (i.e. position, velocity, and attitude) can usually be better determined by combining different navigation technologies (e.g., RF, inertial, and vision-based), their parts and navigation aids (e.g., sensors measuring only distance, velocity, altitude, or attitude) as listed in Tab. 1.3. The combination can be performed on system- or sensor level using different integration strategies. Each fusion technique has its own characteristics and the choice of a specific system is derived from its requirements and application field.

Table 1.3: Navigation systems for direct sensor orientation and navaids

Full navigation solution	Navigation aid
Satellite RF ranging (e.g., GPS, GLONASS)	Heading/attitude: magnetic compass, differential odometry, gyros
Terrestrial RF ranging (e.g., Loran-C, cellular)	Velocity/position: speedometer, accelerometers, etc.
Inertial navigation systems (INS)	Distance: odometer, pedometer, laser
Vision-based systems	Map matching

A simple concept of sensor fusion is schematically depicted in Fig. 1.2 for a case of two sensors. Two distinct sensors sample the same input signal, however, with accuracy that depends on signal frequency. In other words, one sensor reflects good accuracy in the short-term, the other one in the long-term. The optimal fusion is a superposition of sensors' outputs after high-pass and low-pass filtering, respectively.

Although it is possible to integrate any set of technologies, the integration of satellite positioning (e.g., GPS, GLONASS, Galileo) and inertial sensors or INS represents the core of for any integrated systems where reliability and versatility are the major issues. The low cost of global navigation satellite system (GNSS)

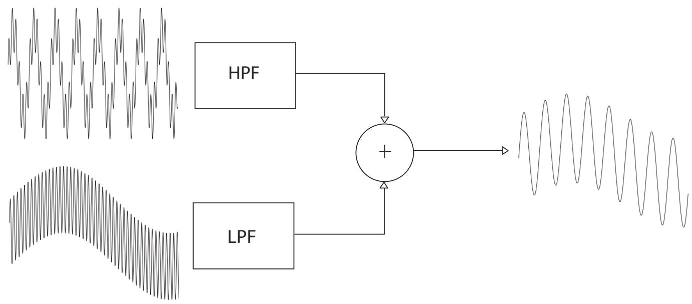

Figure 1.2: Simple example of sensor fusion

receivers, the coverage and reliability of some of them (e.g. GPS), and the decrease in cost of MEMS-based inertial sensors make GNSS and INS the current driving technologies for realizing the benefits offered by integrated navigation systems as schematically shown in Tab. 1.4.

Table 1.4: Inertial navigation vs. GNSS

<table>
<tr><th>INS</th><th>GNSS</th></tr>
<tr><td>Autonomous
High short-term accuracy for position and velocity
Accurate attitude information
Accuracy degrading with time
High measurement update rate
No signal outages
Affected by gravity</td><td>Dependent
High long-term accuracy for position and velocity
Noisy attitude information
Uniform accuracy over time
Low measurement update rate
Subject to loss of lock and cycle slips
Insensitive to gravity</td></tr>
<tr><th colspan="2">GNSS/INS</th></tr>
<tr><td colspan="2">High position and velocity accuracy
Precise attitude determination
High data rate
Bridging of GNSS outages
Cycle-slip detection and correction
Gravity-vector determination</td></tr>
</table>