Survey, Statistical Analysis and Classification of Launched CubeSat Missions with Emphasis on the Attitude Control Method

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Abstract

CubeSat missions have evolved, becoming increasingly capable and complex since their first launch. Relatively high adoption rates and advances in technology allow mission developers to choose from different orbital altitudes, CubeSat configurations, and commercial off-the-shelf (COTS) subsystems. To fulfill particular mission requirements, designers have also developed custom subsystems. In this study, a survey of the attitude control method for each individual launched CubeSat mission is provided, allowing present and future trends to be obtained for specific missions, altitudes, and CubeSat configurations. It is observed that the mission type has an impact on choosing the attitude control method. In particular, Earth observation missions usually require active attitude control with precise pointing requirements. Increased adoption and miniaturization has made active control a more widespread control method in recent years, outnumbering passive control in each year since 2011. In addition, there has been a trend towards more use of larger CubeSats, which has levelled off at the 3U level; 6U configurations are still very rare. The results of this survey and analysis can help developers identify future trends helping them to better address CubeSat community needs. In addition, the provided results can be used to obtain more realistic simulations and CubeSat population models.

1. Introduction

The CubeSat concept was first proposed in 1999 by Jordi Puig-Suari (California Polytechnic State University) and Bob Twiggs (Stanford University). Within 15 years, the concept has been adopted by universities, commercial and civil entities, and military users. The complexity and capabilities of the launched CubeSats have increased, thanks to advancing technology and rising CubeSat popularity, which has made several commercial off-the-shelf (COTS) subsystems available.

One of the many reasons for the CubeSat concept's success is their fast development time, which enables under- and post-graduate students to be involved in spacecraft projects from their inception

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through design and finally to launch and operations—something that is was not possible with traditional spacecraft projects. The availability of a wide range of COTS components helps to achieve this fast development time. In addition, the commercially available CubeSat launchers, such as P-POD (Puig-Suari, 2008), NanoRacks (NanoRacks LLC, 2015), NLAS (NASA, 2013), NPSCuL (DeJesus et al., 2009), ISIPOD (ISIS, 2016), CSD (Hevner et al., 2011), and the Universal Transportation-Deployer Container (Lagno et al., 2016) also helps in finding suitable and readily available launch opportunities, but limit the CubeSat configuration size.

In this study, a survey of the attitude control methods used by all launched CubeSat missions is presented and general trends with respect to the CubeSat mission's parameters are analyzed. The attitude control subsystem (ACS) is the focus of this study, as there is an increasing demand for high performance attitude control, which is a pre-requisite to enable more advanced missions, in particular for many commercial Earth observation missions. In addition, due to the limited CubeSat mass, volume and power, ACS has been one of the least developed subsystems. The ACS has been lagging behind its small satellite class counterparts (as highly capable attitude control systems have traditionally been bulky, heavy, and quite power hungry). There are many experimental concepts (Polat, 2016; Virgili-Llop et al., 2013 and 2016) and missions (Munoz et al., 2011; Sandau et al., 2008) that attempt to increase the ACS capability within the CubeSat standard limitations. However, proven and reliable high performance ACS system, as in traditional small satellites, has yet to be realized in CubeSats. Therefore, by analyzing the selection of ACS method, according to mission type, operational altitude, launch year and CubeSat configuration sizes provides valuable information to CubeSat developers.

In the literature, the survey of CubeSat missions has been conducted for either Low Earth Orbit debris concerns or CubeSat designers' trend analysis. Bouwmeester and Guo have analyzed CubeSat class missions in terms of their subsystems, such as electrical power supply; attitude and orbit determination and control; communication, command, and data handling; and structure (Bouwmeester et al., 2010).

They conclude that most subsystems in CubeSat platforms are advanced except for attitude determination and control subsystems. Swartwout has analyzed the first 100 CubeSat missions in terms of on-orbit performances (Swartwout, 2010) and further investigated the dramatic increase in CubeSat numbers and transformation of CubeSat platform into a professionally-built, useful mission executer (Swartwout, 2011). Finally, NASA Goddard Space Flight Center has published a report about CubeSat data analysis in terms of distribution of satellite classes, users, mass and volume, annual numbers, and rate of successful launches (NASA, 2015). Then, a probabilistic approach has been taken to predict fulfilled missions after successful launches by mass and time in the NASA report.

The survey here provided contains updated data, as of January 1, 2016, and in-depth analysis of the ACS with other mission parameters. The in-depth ACS analysis includes the attitude control methodology selection with respect to mission type, configuration size, launch year, and altitude.

2. Data Collection

Associate Professor at the Space Systems Research Laboratory (SSRL), Saint Louis University, Michael Swartwout, keeps track of all the launched CubeSat missions in an online database (Swartwout, 2016). The database is up-to-date with information such as name, launch date, and size of the CubeSat, type and class of the mission, name of the contractor, ejector and launch vehicle, status of the mission, and functional status of the CubeSat.

Swartwout's database provides a complete chronological list of all CubeSat missions. Some particular information from its database was used as a baseline for this study, namely: the name, size, launch year, and mission status. The mission type information was slightly modified, as will be discussed in the next section. Then, as the core contribution of this study, attitude control methodologies of each mission were added, along with the operational orbit (i.e. altitude, and inclination information), or planned orbit in the case of launch failures.

The desired data pertaining to each individual CubeSat mission was collected from the official mission websites or related academic publications, if present. Some missions, especially missions with failures or military missions, do not have updated or present information about their attitude control methodologies. Therefore, that information was labeled as "Not Available-N/A". In addition, other online satellite databases (Krebs, 2015; ESA, 2015; Lafleur, 2015) were searched for mission information or cross-validation of the already obtained data.

3. Data Summary

CubeSat missions known to the authors to be launched up until January 2016 have been included in this survey. Special attention was paid to obtain ACS, operational altitude, and the orbit's inclination. In addition, a slightly different mission type classification was made, relative to Swartwout's list. Due to the extent of the total mission number (426 ea.), a summary of the collected data is presented in Table 2 (a complete list can be found at the Spacecraft Robotics Laboratory website and in Polat, 2016). The summary list excludes missions that experienced a launch failure or that never achieved communication with the ground. In addition to mission status-related exclusions, some missions that were identical to each other or with mostly N/A information have been excluded from the summary list.

With regard to the Table 2 captions, the serial number (S/N) is kept the same as the complete list for ease of traceability. Launch year, satellite name, size, and mission status information were extracted from Swartwout's list (Swartwout, 2016) as mentioned earlier. Swartwout's mission status classification was used in this study (Table 1).

Table 1. CubeSat Mission Analysis Data Summary

Mission Status	
1	Launch Failure
2	Deployed, but no communication is achieved
3	At least one uplink and downlink is achieved
4	Satellite is performing primary mission requirements
5	Primary mission is achieved

Mission type classification was made with slightly different definitions. First, five different mission types were used in this study: Technology Demonstration (Tech Demo); Scientific; Earth Observation; Military; and Communication (COMM). New concept/technology demonstrations or pre-mission tests of components/systems were included in Tech Demo. Scientific missions include science-related missions such as ionosphere, magnetosphere, or radiation belt observation missions. Earth Observation missions include imaging and tracking missions. If the observation nature of the mission was related with scientific research purposes, those missions were considered Scientific missions. The Military classification was selected for missions purely aiming to achieve military goals. Even if the developer and/or owner of the CubeSat were military entities, the mission was not marked as Military unless it had a military mission objective. For example, the U.S. Naval Academy launched USS Langley CubeSat for technology demonstration of a space-based networking (U.S. Naval Academy, 2014). That mission was considered as Tech Demo, not Military. On the other hand, if the military mission objective was communication-related, that particular mission was considered as Military, not COMM. For instance, TacSat-6 CubeSat by the U.S. Army SMDC (Space and Missile Defense Command) for the ORS (Operationally Responsive Space) office (Krebs, 2015) was a military communication mission, so the mission was labeled as Military, not COMM. Communications missions that were not military have then been included in COMM.

For each mission, ACS information was added to the list with the control actuator types. If found, the number/axis of actuators was added to the attitude control system column. Finally, operational orbit altitude and the orbit inclination of each mission has been added. For highly elliptical orbits, both perigee and apogee altitudes were inserted; otherwise, only one mission operational altitude was used. For missions that experienced a launch failure, the planned altitude was used in this study to see the developer's choice pertaining to mission altitude, allowing us to extract information about the selection of the ACS method.

Table 2. CubeSat Mission Analysis Data Summary

S/N	Launch Year	Satellite Name	Mission Type	Size	Attitude Control System	Orbit's Altitude/ Inclination	Mission Status
5	2003	CUTE-1	Tech Demo	1U	No ACS	820 km / 98.6°	3
7	2003	QUAKESAT 1	Scientific	3U	Passive Magnetic Control	820 km / 98.7°	5
10	2005	UWE-1	Tech Demo	1U	Passive Magnetic Control	700 km / 98.2°	3
26	2006	HITSAT	Tech Demo	1U	Spin Stabilized, 3 x Torque Coils	279x 648 km / 98.3°	4
27	2006	GENESAT	Scientific	3U	Passive Magnetic Control	460 km / 40.5°	5
28	2006	MARSCOM	COMM	1U	Passive Magnetic Control	310 km / 51.6°	5
30	2006	RAFT	COMM	1U	Passive Magnetic Con	300 km / 51.6°	5
32	2007	CAPE 1	Tech Demo	1U	3 x Torque Coils	646x793 km / 98°	3
34	2007	CP 4	Tech Demo	1U	N/A	650 km / 98°	3
35	2007	CSTB 1	Tech Demo	1U	3 x Torque Coils	745 km / 98°	5
38	2008	AAUSAT 2	Scientific	1U	3 x Torque Coils 3 x Momentum Wheels	635 km / 97.2°	5
39	2008	CANX 2	Tech Demo	3U	3 x Torque Coils 1 x Reaction Wheel	635 km / 97.2°	5
40	2008	COMPASS 1	Tech Demo	1U	3 x Torque Coils	635 km / 97.2°	5
41	2008	DELFI C3	Tech Demo	3U	Passive Magnetic Control	635 km / 97.2°	5
42	2008	SEEDS 2	Tech Demo	1U	No ACS	635 km / 97.2°	5
46	2009	KKS-1	Tech Demo	1U	Micro Thruster (3-axis)	670 km / 98°	3
47	2009	AEROCUBE 3	Tech Demo	1U	1-axis Reaction Wheel	432x467 km / 40.4°	3
48	2009	CP 6	Tech Demo	1U	N/A	432x467 km / 40.4°	4
50	2009	PHARMASAT	Scientific	3U	N/A	432x467 km / 40.4°	5
52	2009	DRAGONSAT 2	Tech Demo	1U	N/A	325x332 km / 51.7°	4
53	2009	BEESAT	Tech Demo	1U	3 x Reaction Wheels 6 x Torque Coils	720 km / 98.3°	5
55	2009	SWISSCUBE	Scientific	1U	3 x Torque Coils	720 km / 98.3°	4
58	2010	NEGAI-STAR	Tech Demo	1U	N/A	300 km / 30°	5
61	2010	TISAT 1	Tech Demo	1U	Passive Magnetic Control	635 km / 97.8°	5
62	2010	O/OREOS	Scientific	3U	Passive Magnetic Control	650 km / 72°	5
63	2010	RAX 1	Scientific	3U	Passive Magnetic Control	650 km / 72°	4
66	2010	PERSEUS 001	Tech Demo	1.5U	N/A	279x308 km / 34.5°	5
67	2010	PERSEUS 002	Tech Demo	1.5U	N/A	279x308 km / 34.5°	5
68	2010	PERSEUS 003	Tech Demo	1.5U	N/A	279x308 km / 34.5°	5
69	2010	QBX 1	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	300 km / 34.5°	5
70	2010	QBX 2	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	300 km / 34.5°	5
71	2010	SMDC-ONE 1	COMM	3U	Passive Magnetic Control	300 km / 34.5°	5
72	2011	NANOSAIL-D-002	Tech Demo	3U	Passive Magnetic Control	650 km / 9°	5
76	2011	PSSC-2	Tech Demo	2U	3 x Reaction Wheels 3 x Torque Coils, Thrusters	350 km / 51.6°	5
77	2011	JUGNU	Earth Obs.	3U	4 x Reaction Wheels 3 x Torque Coils	860 km / 20°	4

S/N	Launch Year	Satellite Name	Mission Type	Size	Attitude Control System	Orbit's Altitude/ Inclination	Mission Status
78	2011	AUBIESAT1	Tech Demo	1U	N/A	452x750 km / 102°	3
79	2011	DICE 1	Scientific	1.5U	Spin Stabilized 3 x Torque Coils	820x400 km / 102°	5
80	2011	DICE 2	Scientific	1.5U	Spin Stabilized 3 x Torque Coils	820x400 km / 102°	5
83	2011	RAX-2	Scientific	3U	Passive Magnetic Control	820x400 km / 102°	5
86	2012	MASAT-1	Tech Demo	1U	3 x Torque Coils	354x1450 km / 69.5°	5
90	2012	XATCOBEO	Tech Demo	1U	No ACS	354x1450 km / 69.5°	5
91	2012	AENEAS	Earth Obs.	3U	3 x Reaction Wheels 3 x Torque Coils	770x480 km / 66°	3
92	2012	AEROCUBE 4.0	Tech demo	1U	3 x Reaction Wheels 3 x Torque Coils	770x480 km / 66°	5
93	2012	AEROCUBE 4.5A	Tech demo	1U	3 x Reaction Wheels 3 x Torque Coils	770x480 km / 66°	5
94	2012	AEROCUBE 4.5B	Tech demo	1U	3 x Reaction Wheels 3 x Torque Coils	770x480 km / 66°	5
95	2012	CINEMA 1	Scientific	3U	Spin Stabilized 2 x Torque Coils	770x480 km / 66°	3
96	2012	CP 5	Tech Demo	1U	N/A	770x480 km / 66°	3
97	2012	CSSWE	Scientific	3U	Passive Magnetic Control	770x480 km / 66°	5
98	2012	CXBN	Scientific	2U	Spin Stabilized 3 x Torque Coils	770x480 km / 66°	3
99	2012	RE (STARE)	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	500 km / 66°	3
100	2012	SMDC ONE 1.1	COMM	3U	Passive Magnetic Control	770x480 km / 66°	5
101	2012	SMDC ONE 1.2	COMM	3U	Passive Magnetic Control	770x480 km / 66°	5
103	2012	FITSAT-1	Tech Demo	1U	Passive Magnetic Control	420 km / 51.6°	5
104	2012	RAIKO	Tech Demo	2U	3 x Torque Coils	420 km / 51.6°	5
105	2012	TECHEDSAT	Tech Demo	1U	Passive Magnetic Control	350 km / 51.6°	4
107	2013	AAUSAT 3	Earth Obsv.	1U	3 x Torque Coils	780 km / 98.5°	5
108	2013	STRAND-1	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	786 km / 98.5°	4
109	2013	BEESAT 2	Tech Demo	1U	3 x Reaction Wheels 3 x Torque Coils	557x581 km / 98.5°	4
111	2013	DOVE 2	Tech Demo	3U	3 x Torque Coils	575 km / 64.8°	5
113	2013	SOMP	Scientific	1U	Passive Magnetic Control aided by 3 x Torque Coils	600 km / 64.8°	3
114	2013	PHONESAT 1A	COMM	1U	N/A	250 km / 51.6°	5
115	2013	PHONESAT 1C	COMM	1U	N/A	250 km / 51.6°	5
116	2013	DOVE 1	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	250 km / 51.6°	5
117	2013	PHONESAT 1B	COMM	1U	N/A	250 km / 51.6°	5
118	2013	CUBEBUG-1	Tech Demo	2U	Nano Reaction Wheel	630 km / 98°	4
119	2013	NEE 01 PEGASO	Tech Demo	1U	N/A	630 km / 98°	4
120	2013	TURKSAT 3USAT	COMM	3U	Passive Magnetic Control	630 km / 98°	3

S/N	Launch Year	Satellite Name	Mission Type	Size	Attitude Control System	Orbit's Altitude/ Inclination	Mission Status
121	2013	ESTCUBE-1	Tech Demo	1U	3 x Torque Coils	670 km / 98º	4
122	2013	POPACS 1/2/3	Tech Demo	3U	N/A	324x1480 km / 81°	4
123	2013	ARDUSAT 1	Scientific	1U	N/A	410 km / 51.6°	3
124	2013	ARDUSAT X	Scientific	1U	N/A	410 km / 51.6°	4
125	2013	PICODRAGON	Tech Demo	1U	N/A	410 km / 51.6°	4
127	2013	CAPE 2	Tech Demo	1U	N/A	400 km / 40.5°	4
131	2013	FIREFLY	Scientific	3U	Gravity Gradient 3 x Torque Coils	500 km / 40.5°	4
134	2013	KYSAT II	Earth Obs.	1U	Passive Magnetic Control	500 km / 40.5°	4
135	2013	LUNAR	Tech Demo	1U	Diff. Chemical Thruster	500 km / 40.5°	4
136	2013	NPS-SCAT	Tech Demo	1U	N/A	500 km / 40.5°	3
137	2013	ORS TECH 1	Military	3U	Pitch-axis Momentum Wheel + 4 x Torque Coils	500 km / 40.5°	4
139	2013	ORSES	Military	3U	N/A	500 km / 40.5°	4
140	2013	PHONESAT 2.4	COMM	1U	6 x Torque Coils 3 x Reaction Wheels	500 km / 40.5°	3
141	2013	PROMETHEUS1.1	Military	1.5U	N/A	500 km / 40.5°	4
149	2013	SENSE SV1	Military	3U	4 x Reaction Wheels 3 x Torque Coils	500 km / 40.5°	4
150	2013	SENSE SV2	Military	3U	4 x Reaction Wheels 3 x Torque Coils	500 km / 40.5°	4
158	2013	DELFI-N3XT	Tech Demo	3U	3 x Reaction Wheels 3 x Torque Coils	600 km / 97.6°	4
160	2013	FIRST-MOVE	Tech Demo	1U	Passive Magnetic Control	630 km / 97.6	3
161	2013	FUNCUBE 1	COMM	1U	N/A	670 km / 97.6	4
162	2013	GATOS (GOMX 1)	Earth Obs.	2U	3 x Torque Coils	600 km / 97.6	4
164	2013	HUMSAT D	COMM	1U	No ACS	600 km / 97.6°	4
166	2013	NEE02 KRYSAOR	N/A	1U	N/A	600 km / 97.6°	4
168	2013	PUCP-SAT 1	Tech Demo	1U	N/A	600 km / 97.6°	3
170	2013	UWE 3	Tech Demo	1U	3 x Torque Coils 3 x Reaction Wheels	600 km / 97.6°	4
171	2013	VELOX-P 2	Tech Demo	1U	3 x Torque Coils	600 km / 97.6°	4
177	2013	FIREBIRD 1	Scientific	1.5U	Passive Magnetic Control	467x883 km / 120.5°	4
178	2013	FIREBIRD 2	Scientific	1.5U	Passive Magnetic Control	467x883 km / 120.5°	4
179	2013	IPEX	Tech Demo	3U	Passive Magnetic Control	467x883 km / 120.5°	4
180	2013	M-CUBED-2	Earth Obs.	1U	Passive Magnetic Control	467x883 km / 120.5°	4
181	2013	SMDC-ONE 2.3	Military	3U	Passive Magnetic Control	300 km / 120.5°	4
182	2013	SMDC-ONE 2.4	Military	3U	Passive Magnetic Control	300 km / 120.5°	4
183	2013	SNAP 1	Tech Demo	1U	3 x Torque Coils Momentum Wheel	467x883 km / 120.5°	4
184	2013	TACSAT-6	Military	3U			4
185 210	2014	FLOCK-1-01 FLOCK-1-26	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	370x430 km / 51.6°	5
215	2014	OPUSAT (COSMOZ)	Tech Demo	1U	2 x Torque Coils	380 km / 65°	3

S/N	Launch Year	Satellite Name	Mission Type	Size	Attitude Control System	Orbit's Altitude/ Inclination	Mission Status
					Spin Stabilized		
217 218	2014	FLOCK-1-27 FLOCK-1-28	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	370x430 km / 51.6°	5
220	2014	LITUANICASAT 1	Tech Demo	1U	Passive Magnetic Control	370x430 km / 51.6°	4
224	2014	KICKSAT 1	Tech Demo	3U	Spin Stabilized	325x315 km / 51.6°	3
225	2014	PHONESAT 2.5	Tech Demo	1U	3 x Torque Coils 3 x Reaction Wheels	325x315 km / 51.6°	5
226	2014	SPORESAT	Scientific	3U	Passive Magnetic Control	400 km / 51.6°	5
227	2014	TSAT (TESTSAT-LITE)	Scientific	2U	Aerodynamic Stabilized	300 km / 51.6°	4
228	2014	AEROCUBE 6A	Scientific	0.5U	3 x Torque Coils	620x480 km / 97.9°	4
229	2014	AEROCUBE 6B	Scientific	0.5U	3 x Torque Coils	620x480 km / 97.9°	4
230	2014	ANTELSAT	Earth Obs.	2U	3 x Torque Coils	630 km / 97.9°	4
233 243	2014	FLOCK-1C-01 FLOCK-1C-11	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	605x620 km / 97.9°	4
245	2014	NANOSATC-BR 1	Scientific	1U	Passive Magnetic Control	630 km / 97.9°	3
247	2014	PERSEUS-M 1	Earth Obs.	6U	N/A	620 km / 97.9°	4
249	2014	POLYITAN 1	Tech Demo	1U	N/A	620 km / 97.9°	4
250	2014	POPSAT-HIP	Earth Observation	3U	3 x Torque Coils 12 x Micro Thrusters	600 km / 97.9°	4
251	2014	QB50P1 (EO-79)	Tech Demo	2U	3 x Torque Coils Momentum Wheel	620x480 km / 97.9°	4
252	2014	QB50P2 (EO-80)	Tech Demo	2U	3 x Torque Coils Momentum Wheel	620x480 km / 97.9°	4
253	2014	TIGRISAT	Tech Demo	3U	3 x Torque Coils	600x700 km / 97.8°	4
254	2014	VELOX I-NSAT	Tech Demo	3U	3 x Torque Coils 3 x Reaction Wheels	650x700 km / 98.1°	3
255	2014	UKUBE 1	Tech Demo	3U	3 x Torque Coils	635 km / 98.3°	4
257 274	2014	FLOCK-1B	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	370x430 km / 51.6°	4
304	2015	EXOCUBE (CP10)	Scientific	3U	Gravity Gradient Pitch Momentum Wheel 3 x Torque Coils	440x670 km / 99°	3
305	2015	FIREBIRD-IIA	Scientific	1.5U	Passive Magnetic Control	440x670 km / 99°	4
307	2015	GRIFEX	Tech Demo	3U	N/A	460x670 km / 99°	4
309 318	2015	FLOCK-1B FLOCK-1D	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	370x430 km / 51.6°	4
323 324	2015	FLOCK-1B	Earth Obs.	3U	3 x Torque Coils 3 x Reaction Wheels	370x430 km / 51.6°	4
329	2015	PSAT A	COMM	3U	3 x Torque Coils	355x700 km / 55°	4
330	2015	BRICSAT-P	Tech Demo	1.5U	4 x Thrusters Passive Magnetic Control	355x700 / 55°	3
334	2015	LIGHTSAIL A	Tech Demo	3U	3 x Torque Coils Momentum Wheel	355x700 km / 55°	5
368	2015	GOMX-3	COMM	3U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	3
369	2015	AAUSAT-5	Tech Demo	3U	3 x Torque Coils	400 km / 51.6°	3

S/N	Launch Year	Satellite Name	Mission Type	Size	Attitude Control System	Orbit's Altitude/ Inclination	Mission Status
370 379	2015	FLOCK 2B (01-10)	Earth Obs.	3U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	4
380	2015	AEROCUBE 5C	Tech Demo	1.5U	N/A	500x800 km / 63°	3
381	2015	AEROCUBE 7	Tech Demo	1.5U	3 x Reaction Wheels 3 x Torque Coils	500x800 km / 63°	3
382	2015	FOX 1A	COMM	1U	Passive Magnetic Control	500x800 km / 63°	4
383	2015	BISONSAT	Scientific	1U	Passive Magnetic Control	500x800 km / 63°	4
384	2015	ARC-1	Tech Demo	1U	3 x Torque Coils	500x800 km / 63°	3
385	2015	SNAP-3 ALICE	Military	3U	Thrusters	500x800 km / 63°	3
387	2015	SNAP-3 EDDIE	Military	3U	Thrusters	500x800 km / 63°	3
390	2015	SNAP-3 JIMI	Military	3U	Thrusters	500x800 km / 63°	3
393 394	2015	FLOCK 2B (13-14)	Earth Obs.	3U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	4
409	2015	BEVO 2	Tech Demo	3U	Cold Gas Propulsion 3 x Reaction Wheels 3 x Torque Coils	415 km / 51.6°	4
410	2015	MINXSS	Scientific	3U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	4
411	2015	STMSAT 1	Tech Demo	1U	Passive Magnetic Control	415 km / 51.6°	3
412	2015	NODES 1	Tech Demo	1.5U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	3
413	2015	NODES 2	Tech Demo	1.5U	3 x Reaction Wheels 3 x Torque Coils	400 km / 51.6°	3
414 425	2015	FLOCK 2E (1-12)	Earth Obs.	3U	3 x Reaction Wheels 3 x Torque Coils	415 km / 51.6°	3

4. Data Analysis

From the data shown in the previous table it can be clearly seen that many of the early CubeSats had basic, low performance ACS systems, mainly relying on passive magnetic stabilization (White et al., 1961; Martinelli and Peña, 2005). Due to its hardware and control law simplicity, active magnetic ACS (Stickler and Alfriend, 1976; Junkins 1981)—using magnetic torques—quickly became the de-facto standard, and is still dominant for missions not requiring strict pointing requirements. With this type of active magnetic ACS, a CubeSat can detumble and later control its attitude within a few degrees of the target attitude. Spin stabilization and the inclusion of momentum wheels have been used in a handful of cases to increase the stability of the system (Xiang et al., 2012).

Recent advances in miniaturization have enabled CubeSats to be equipped with reaction wheels, providing greater agility and pointing accuracy (Candini et al., 2012). With current commercial state-of-the-art systems, sub-degree pointing accuracy and slew rates >10 deg/sec (3U CubeSat) can be achieved. Such state-of-the-art COTS ACS systems take less than 1U and include three reaction wheels and three magnetic torquers, as well as the associated attitude determination equipment (e.g., start-tracker, sun sensors, angular velocity sensors, and magnetometer) and control computers (Hegel, 2016). Other generally experimental ACS concepts have also been flown, including Control Moment Gyroscopes, partial aerodynamic stabilization, and different types of cold/hot gas propulsion. More information on the mathematical foundations and basic differences

among the most common attitude and control methods can be found in Wie's work (2008).

Although miniaturization has enabled CubeSats to use many of the ACS systems traditionally reserved for larger spacecraft (i.e., reaction wheels), the performance level offered by larger systems has yet to be matched. Among other technological reasons, some of these ACS systems rely on the components size to provide the required actuation (e.g., the reaction wheel inertia is tied to the angular momentum storage capability) and to provide the same performance on a smaller scale, the physical limitations imposed by smaller components will need to be overcome with advances in other fields (e.g., larger reaction wheel maximum spin raters can be used to offer higher angular momentum storage capability using smaller wheels) (Zwyssig et al., 2014). An area where the miniaturization has not yet made its way towards CubeSats is Control Moment Gyroscopes (CMGs). Although a CMG technology demonstration was flown on SwampSat (Muñoz et al., 2011) CMG use is not yet widespread despite of their potential benefits to spacecraft agility (Oppenheimer et al., 2008; Blocker, 2008; Votel and Sinclair, 2012; Leve et al., 2015).

During the data analysis, one particular CubeSat constellation, Flock by Planet Labs (Planet Labs, 2015) stood up among the others, as it has launched 153 nearly identical CubeSats. Therefore, Flock constellation numbers are distinctly highlighted in the figures for better evaluation of the data.

In Figure 1, it is noticeable that the CubeSat concept is becoming more common and widespread. Especially in the year 2013, the number of CubeSats launched increased dramatically. During the last three years, the number of launched CubeSats accounts for 75% of all the 426 missions launched since 2002.

Among all six different CubeSat configuration sizes—0.5U, 1U, 1.5U, 2U, 3U and 6U—the 3U configuration, with 229 missions, is the most often selected. The 3U size accounts for 53% of all missions (Figure 2). Even though the original CubeSat configuration is 1U, as can be seen in Figure 3, 3U missions outnumbered the 1U configuration (229 to 133) in the last two years. The 3U provides a larger volume, therefore allowing packing more components (sub-

systems or payload), and thus achieving more challenging mission objectives. However, 6U, which is even larger than 3U, has not shown that popularity yet, with only three launched examples (Figure 2). The second most popular configuration is 1U, with a total of 133 launched CubeSats (Figure 2). In recent years, the relative use of the 1U configuration has been declining, while the 1.5U and 2U configurations have seen higher adoption rates (Figure 3). The QB50 planned constellation, which plans to launch roughly 50 2U CubeSats, may bump the 2U size category to the second most commonly used in the next few years (Muylaert et al., 2009).

It is also interesting to see the distribution of CubeSat missions with respect to their primary mission type (Figure 4). Even though Earth observation accounts for the majority of the missions (due to the Flock constellation), CubeSats are still widely used as technology demonstration platforms. However, the failure rate of the technology demonstration mission is still quite high, with 46% of these missions not achieving mission requirements (Figure 5). Besides the launch failures, one fourth of all launched CubeSats failed to perform and operate in the harsh environment of space. On the other hand, more than half of the missions ended up successfully pioneering future missions.

Most CubeSats have been launched into an operational altitude below 500 km (Figure 6). It must be noted that CubeSat missions are launched as secondary payloads (piggybacking), and the altitude and orbit type are determined by the primary payload; thus, most CubeSats have little to no influence on selecting the orbit (they can just subscribe to a launch with a primary vehicle that has an acceptable orbit for their mission). For the moment, all CubeSats have been launched to Low Earth Orbit, with the majority being inserted into the 350–700 km altitude regime (76% of all missions). The low number of launches (3% of all missions) to altitudes below 300 km can be seen in Figure 5, and is mostly due to both short lifetime and high disturbances.

With regard to ACS, CubeSat platforms encompass all different type of components and methods (Figure 7). Micro- or nano-reaction wheels are the second most selected attitude control component,
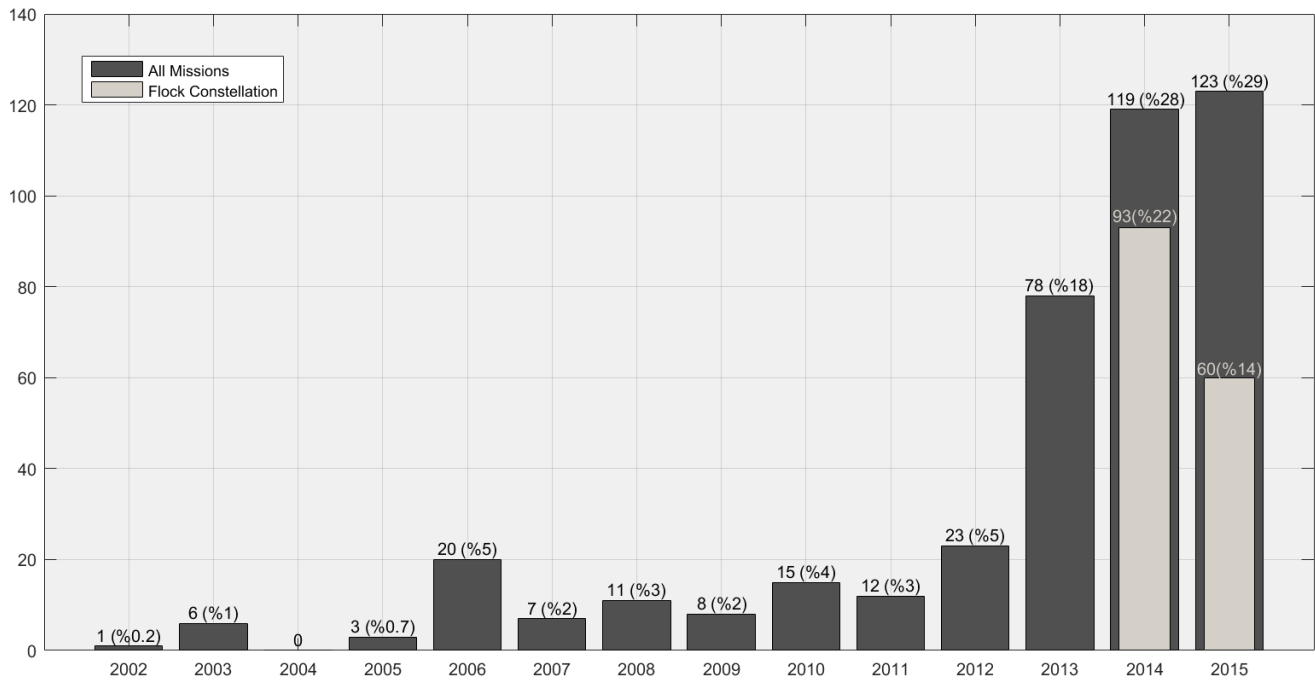
Figure 1. Number of launched CubeSat missions with respect their launch year. Numbers indicate total amount of CubeSats launched that year and in parenthesis there is the percentage with respect to the total number of CubeSats launched.
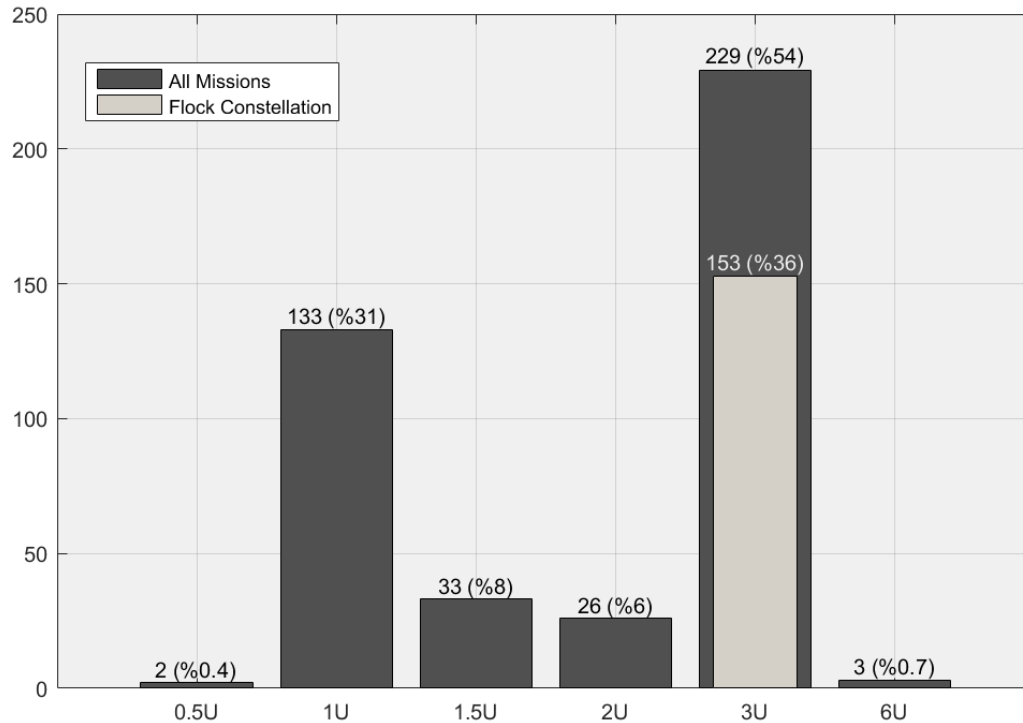

Figure 2. CubeSat configuration size distribution. Numbers indicate total amount of CubeSats launched for that size category and in parenthesis there is the percentage of CubeSats launched in that size category with respect to the total number of CubeSats.
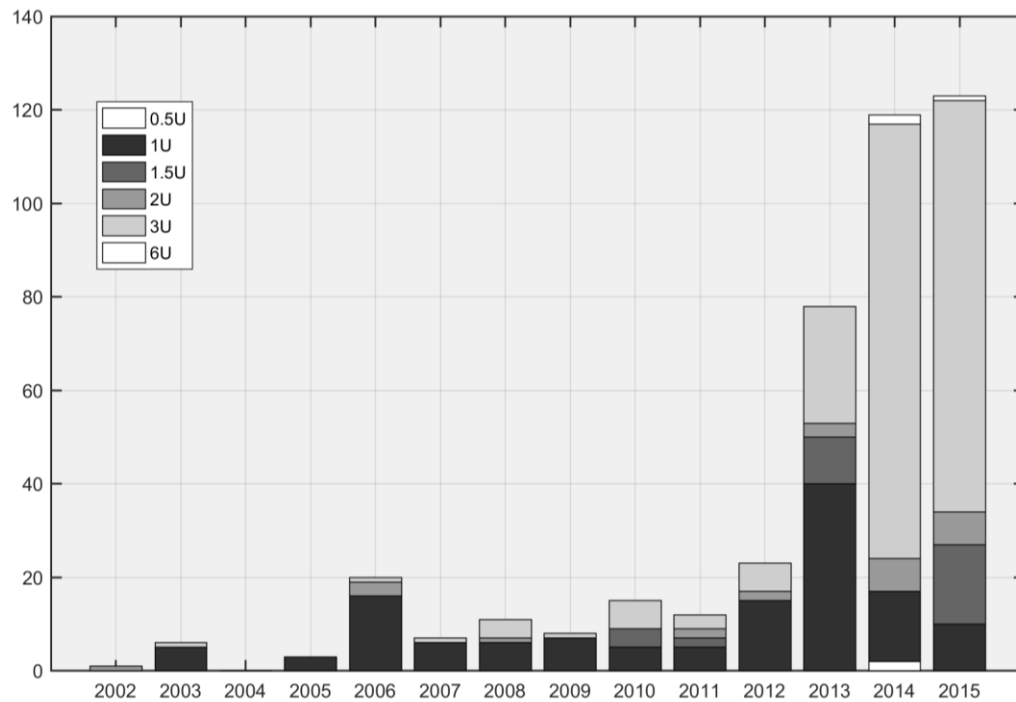
Figure 3. CubeSat configuration sizes with launch years. The vertical bars illustrate different configuration sizes for that year with increasing size order from the bottom to top.
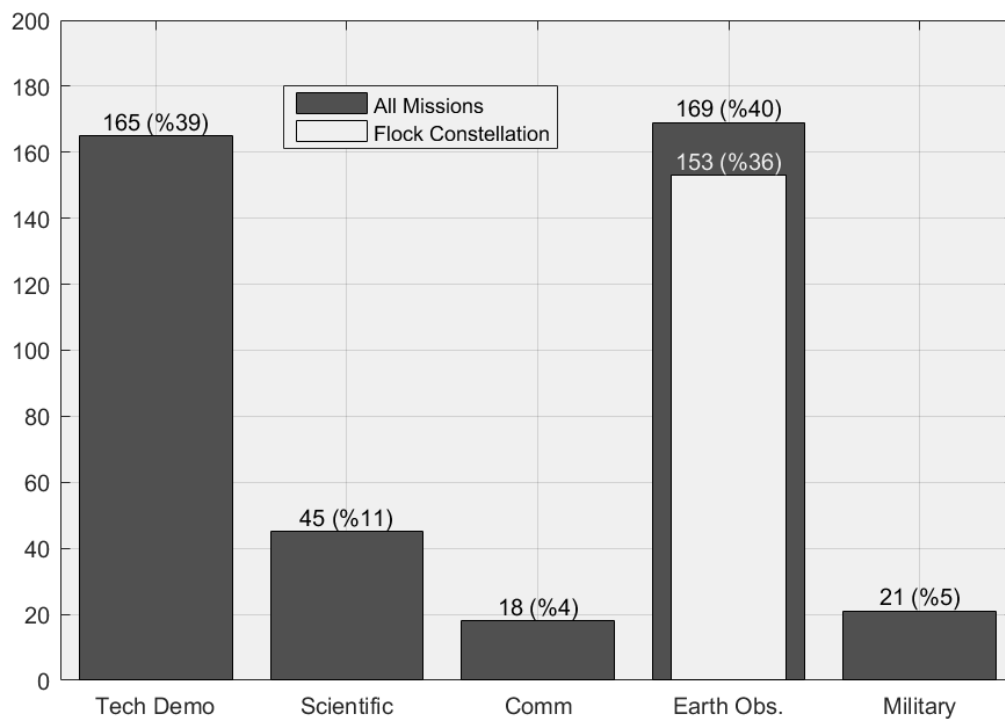
Figure 4. CubeSat mission types. Numbers indicate total amount of CubeSats launched for that application and in parenthesis there is the percentage with respect to the total number of CubeSats launched.
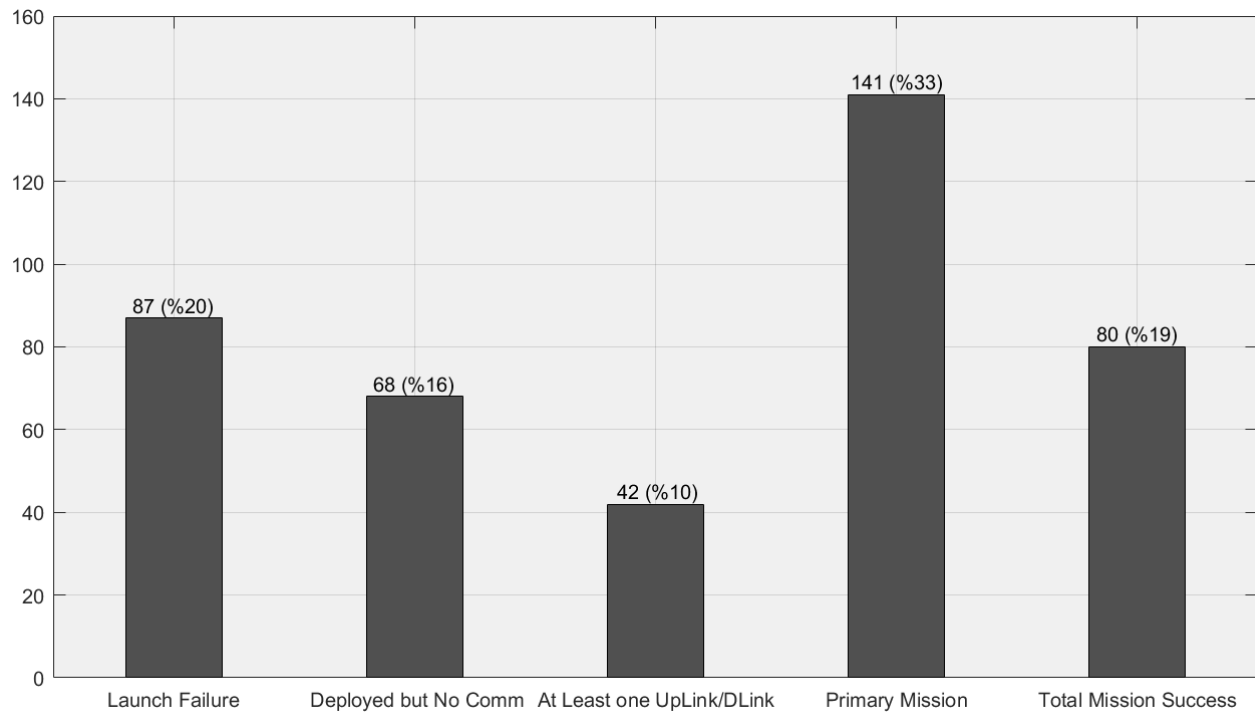
Figure 5. CubeSat mission status. Numbers indicate total amount of CubeSats in each operational status and in parenthesis there is the percentage with respect to the total number of CubeSats launched.
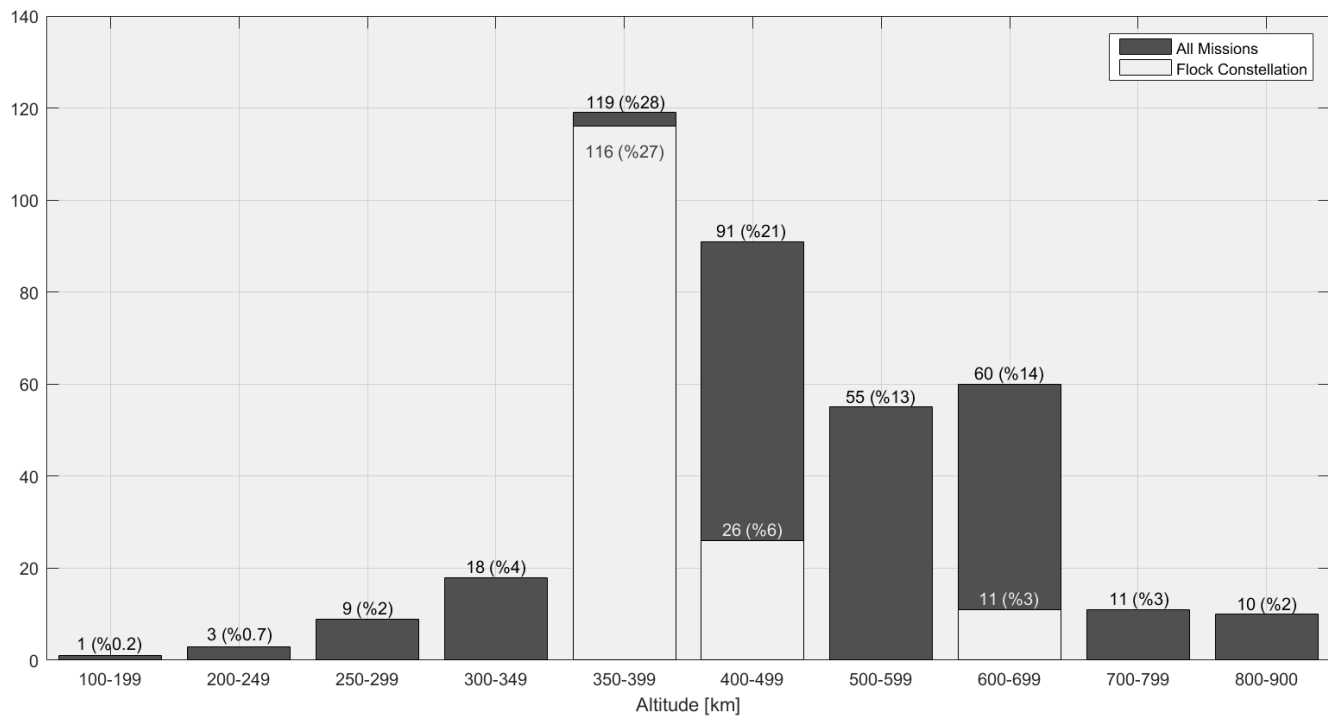
Figure 6. CubeSat mission altitudes. Numbers indicate total amount of CubeSats launched for that altitude range and in parenthesis there is the percentage with respect to the total number of CubeSats launched.
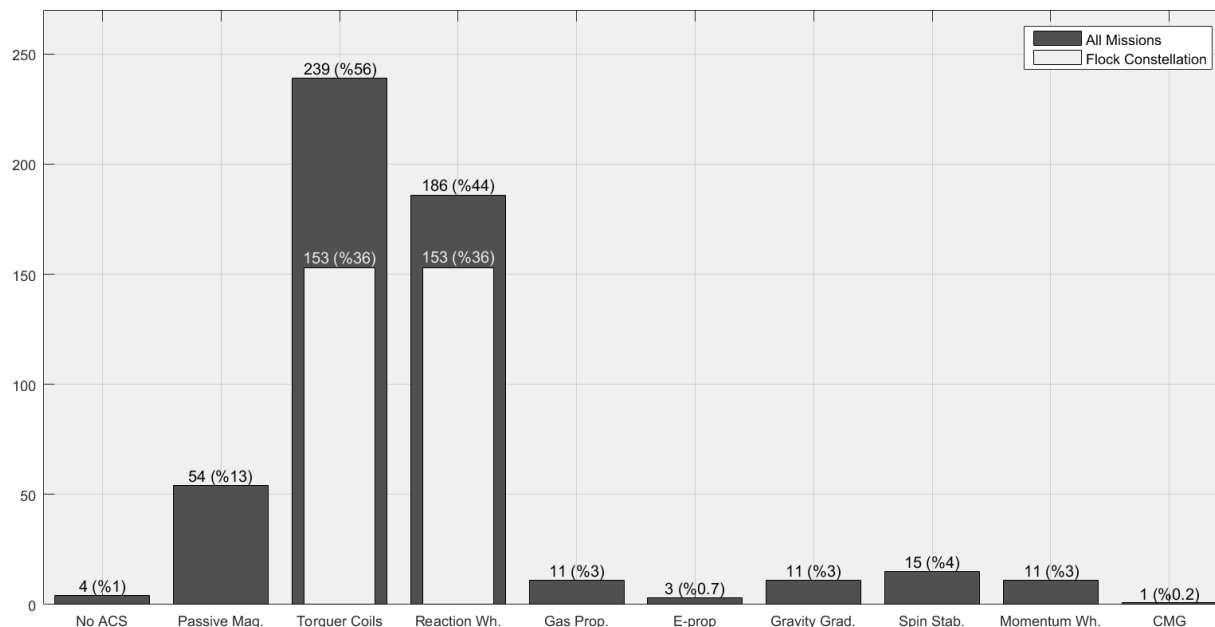
Figure 7. CubeSat attitude control methods/components. Numbers indicate total amount of CubeSats launched for that ACS and in parenthesis there is the percentage with respect to the total number of CubeSats launched.

mostly accompanied by magnetic torquer coils for momentum management. Reaction wheels enable active control, and eventually better mission performances. However, torquer coils are the most used component for their relatively simpler design and implementation requirements. Although magnetic torquer coils provide less pointing accuracy than reaction wheels, they are also providing active control over the CubeSat. The third most selected method is the passive magnetic control. The missions with less or no pointing requirements choose passive magnetic control, as it provides some predicted attitude of the CubeSat. There are also some specific methods or components that were used by different missions, such as gas or electric propulsion, gravity gradient, spin stabilization, and even CMGs. Those individual methods or components are not as widely used as torquer coils, reaction wheels, or passive magnetic control.

The ACS selection changed dramatically in the last four years. Eighty-eight percent of all missions with active control were launched in the last four years. The ratio of active control to passive control is another indicator of this trend shift. The ratios in the last five years are: 2 to 3 in 2011; 4 to 3 in 2012; 2 to 1 in 2013; 12 to 1 in 2014; and lastly, 11 to 1 in 2015 (Figure 8).

CubeSat size is also correlated with the selection of the ACS. As it can be seen in Figure 9, 3U configurations were used mostly with active control (81% of all 3U configurations), whereas 1U configurations had almost equal number of active and passive control methodologies (40 and 38 missions, respectively). It is obvious that if active control is required (requiring more components), then a larger CubeSat size will be generally needed.

The ACS and operating altitude have no correlation (Figure 10). The mission type is in general a more important driving factor. As it can be seen in Figure 11, each mission type has its own ACS distribution, as each mission type usually requires a different level of attitude control complexity. Communication and Earth observation missions show these results in two different ways. Eighty-nine percent of Earth observation missions chose active control, because imaging requires strict pointing requirements. On the other hand, the ratio of active to passive control is approximately 1 to 3 in communication missions, since omni-directional antennas do not require high pointing accuracy. In addition, due to the wide
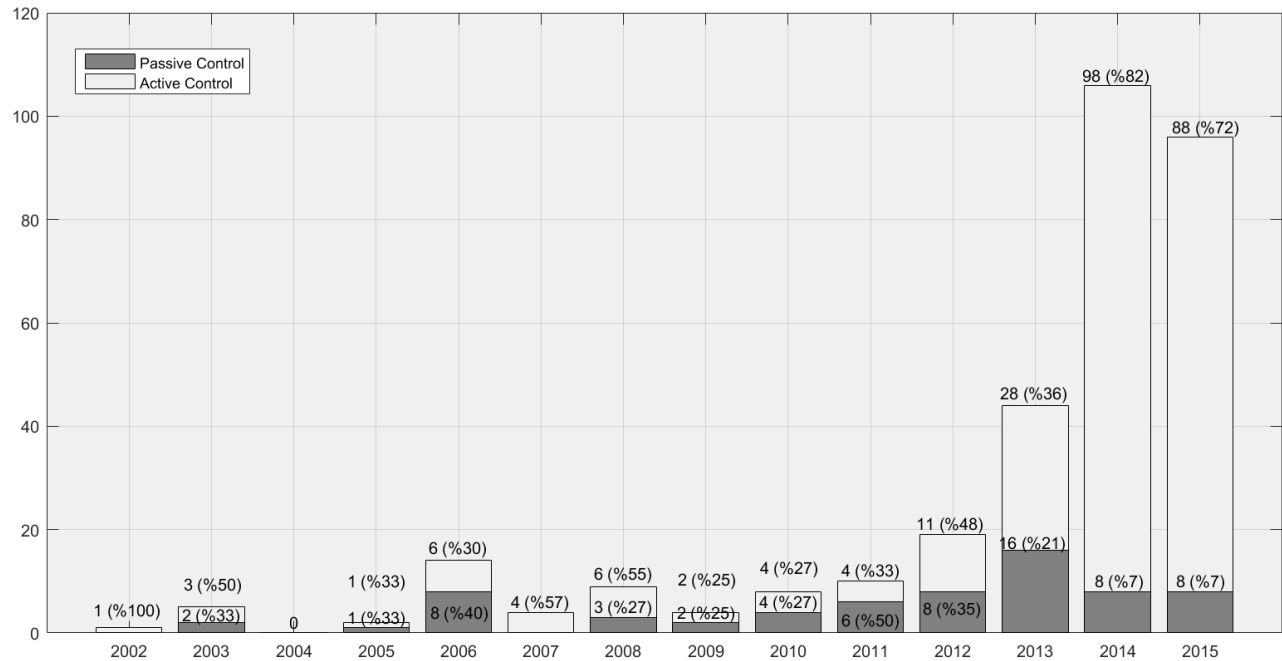
Figure 8. CubeSat attitude control methodologies with launch years. Numbers indicate total amount of CubeSats launched for that ACS band and in parenthesis there is the percentage with respect to the number of CubeSats launched in that specific year. As some missions do not have available ACS information, the percentages may not add to 100%.
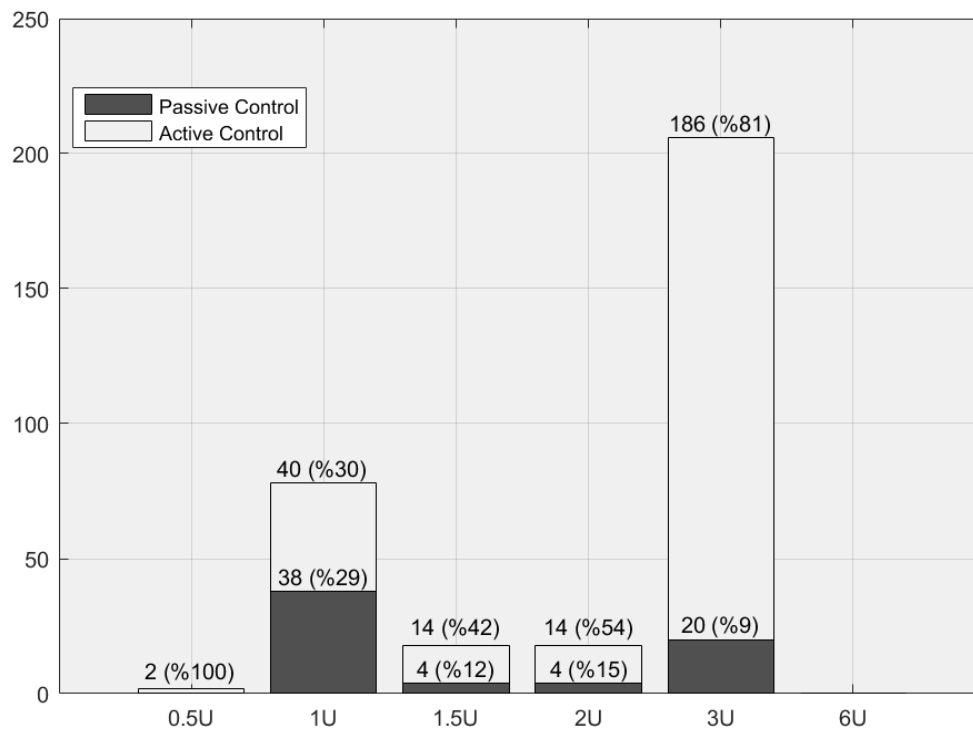

Figure 9. CubeSat attitude control methodologies with configuration sizes. Numbers indicate total amount of CubeSats launched for ACS band and in parenthesis there is the percentage with respect to the total number of CubeSats in that size band. As some missions do not have available ACS information, the percentages may not add to 100%.
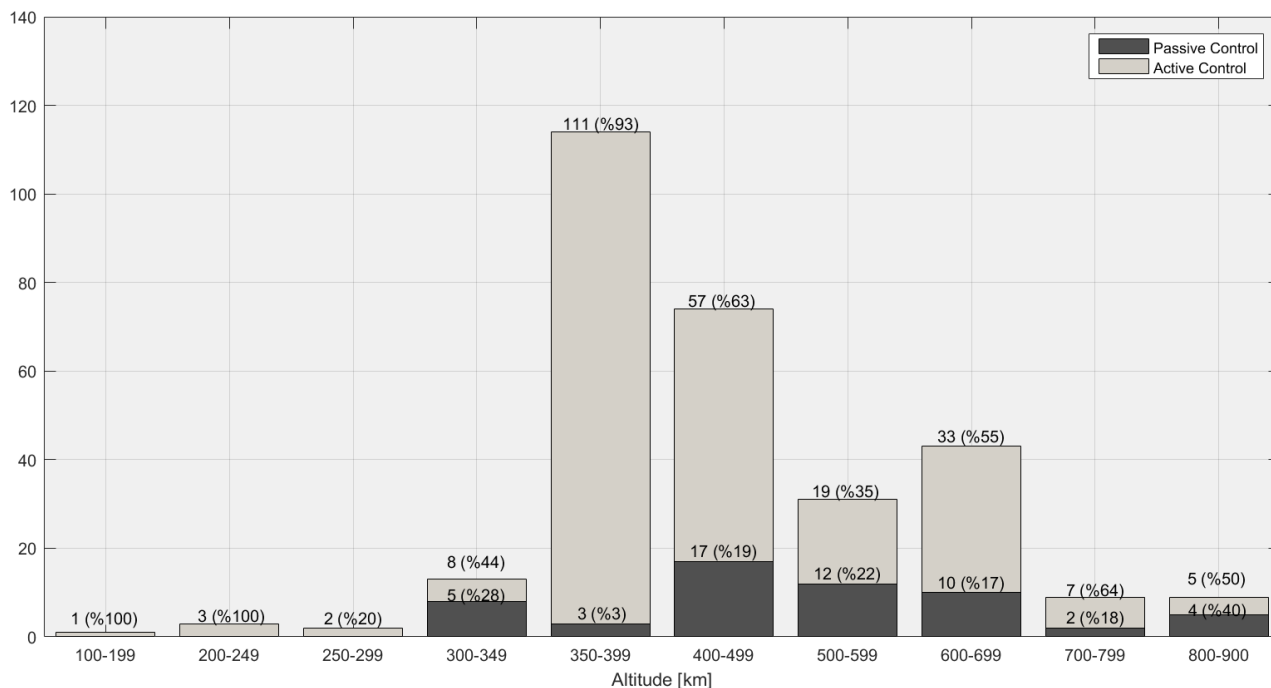
Figure 10. CubeSat attitude control methodologies with altitude. Numbers indicate total amount of CubeSats launched for that ACS band and in parenthesis there is the percentage with respect to the total number of CubeSats launched in that altitude range. As some missions do not have available ACS information, the percentages may not add to 100%.
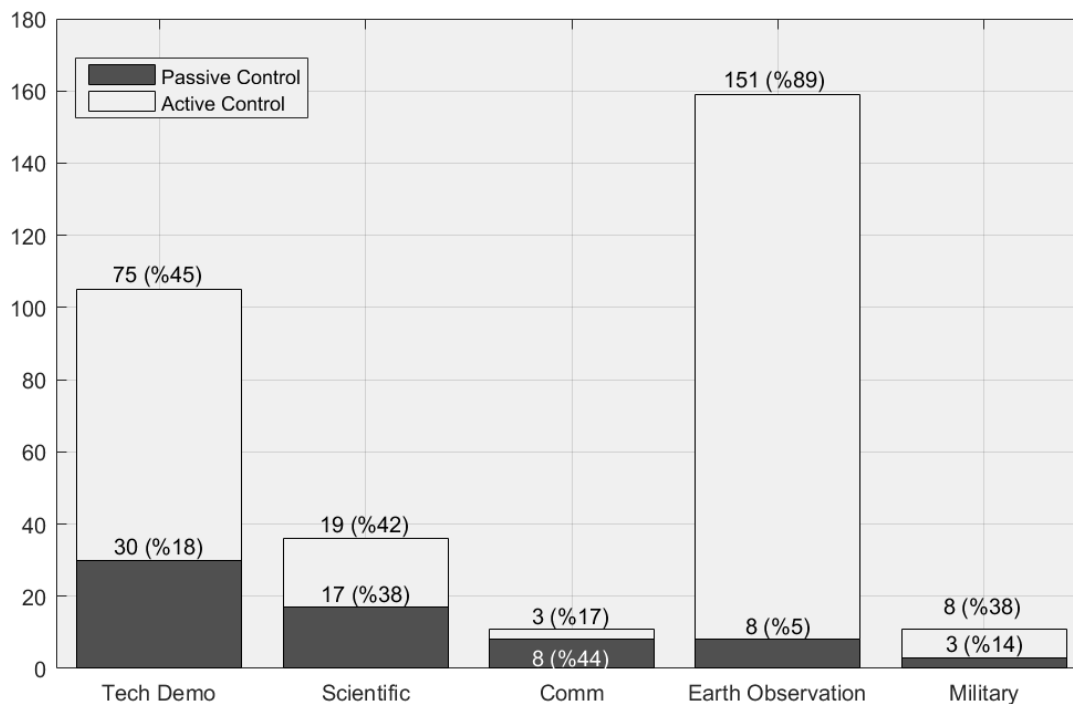

Figure 11. CubeSat attitude control methodologies with mission types. Numbers indicate total amount of CubeSats launched for that ACS band and in parenthesis there is the percentage with respect to the total number of CubeSats launched in that mission type. As some missions do not have available ACS information, the percentages may not add to 100%.

range of mission requirements, scientific missions selected active and passive ACS in an almost equal proportion. In contrast, technology demonstration missions, also exhibiting a wide range of mission requirements mainly selected active control over passive control (3 to 1).

5. Discussion and Future Trends

There is clear trend towards active attitude control for future CubeSat missions. With regard to configuration sizes, the 3U configuration is currently the most selected size (Figure 2), and it appears that it will continue to be in the near future. Although there have been many proposed 6U missions, launched 6U CubeSats are still very rare. As mentioned earlier, larger configurations mostly use active control methods (Figure 9). Earth observation missions represent most of the launched CubeSat missions, closely followed by technology demonstration missions (Figure 3). For Earth observation missions, ACS is mostly used active control (Figure 11). Finally, every year the active control percentages have been increasing for CubeSat missions (Figure 8), mostly due to more demanding missions and advancing technology and wider availability of advanced COTS ACS subsystems. It appears that, for these reasons, active ACS adoption will continue to increase.

This increase in active control usage may result in more advance and challenging missions. As technology matures, a drop in failure rates is expected (Figure 4). Moreover, the better control authority over the CubeSat with active control may enable the developers to design CubeSat for lower altitudes, to exploit the advantage of operating closer to Earth, such as shorter range, better resolution, short revisit, economical launch costs, and efficient debris mitigation processes, etc.

6. Conclusion

Increasing interest in the CubeSat concept shows itself in the launch numbers and in the wide variety of missions. The adoption of CubeSats for more advanced missions is forcing them to adopt active control and this trend is likely to continue. Even though

many newly proposed CubeSats use the 6U configuration, the number of launched 6U CubeSats is still very small, with the 3U configuration dominating the CubeSat population. The trend to larger sizes has also helped the adoption of active control. Reaction wheels working in tandem with torquer coils, dominates the attitude control subsystem developer choices.

References

Blocker, A., Litton, C., Hall, J. et al. (2008): TINYSCOPE – The Feasibility of a 3-Axis Stabilized Earth Imaging CubeSat from LEO, presented at the Ann. AIAA/USU Conf. on Small Satellites, Logan, UT, Paper SSC08-X-4.

Bouwmeester, J. and Guo, J. (2010): Survey of Worldwide Pico- and Nanosatellite Missions, Distributions and Subsystem Technology. *Acta Astronautica*, Vol. 67 (7), pp. 854–862.

Candini, G. P., Piergentili, F., and Santoni, F. (2012): Miniaturized Attitude Control System for Nanosatellites. *Acta Astronautica,* Vol. 81(1), pp. 325–334.

DeJesus, A. et al. (2009): NPS CubeSat Launcher (NPSCuL) Program Update, presented at 2009 CubeSat Developers Workshop, San Luis Obispo, CA.

ESA. "Earth Observation Portal" (2016): Available at: https://directory.eoportal.org/web/eoportal/satellite-missions (last accessed January 5, 2016).

Hegel, D. (2016) FlexCore: Low-Cost Attitude Determination and Control Enabling High-Performance Small Spacecraft, in *Proc. AIAA/USU Conf. on Small Satellites*, Paper SSC16-X-7.

Hevner, R. et al. (2011): An Advanced Standard for CubeSats, presented at 25th Ann. AIAA/USU Conf. on Small Satellites, Logan, UT.

ISIS. "ISIPOD CubeSat Deployer" (2016): Available at: http://www.isispace.nl/brochures/ISIS_ISIPOD_Brochure_v.7.11.pdf (last accessed January 30, 2016).

Junkins, J. L., Carrington, C. K., and Williams, C. E. (1981): Time-optimal Magnetic Attitude Maneuvers. *J. of Guidance, Control, and Dynamics*, Vol. 4(4), pp. 363-368.

Krebs, G. D. "Gunter's Space Page" (2016): Available at: http://space.skyrocket.de/index.html (last accessed January 5, 2016).

Lafleur, C. "Spacecraft Encyclopedia" (2016): Available at: http://claudelafleur.qc.ca/Spacecrafts-index.html#Table-1 (last accessed January 5, 2016).

Lagno, O., Lipatnikova T., and Yudintsev V., (2016): Piggyback Payloads on the Launch Vehicles by JSC SRC Progress, presented at II IAA Latin American CubeSat Workshop, February 28 – March 2, Oceania Convention Centre Florianópolis, Brazil IAA-BR-02-03.

Leve, F. A., Hamilton, B. J., and Peck, M. A. (2015): *Spacecraft Momentum Control Systems* (Vol. 1010). Springer.

Martinelli, M. I. and Peña, R. S. S. (2005): Passive 3-axis Attitude Control of MSU-1 Pico-satellite. *Acta Astronautica*, Vol. 56(5), pp. 507–517.

Muñoz, J. D. et al. (2011): High Fidelity Simulation of SwampSat Attitude Determination and Control System, presented at 21st AAS/AIAA Space Flight Mechanics Meeting, New Orleans, LA.

Muylaert, J.-M., Reinhard, R., Asma, C. O. et al. (2009): QB50, An International Network of 50 CubeSats for Multi-point, In-situ Measurements in the Lower Thermosphere and Re-entry research, in *Proc. Atmospheric Science Conf.*, Barcelona, Spain, September 7–11.

NanoRacks LLC. "Small Satellite Deployment" (2015): Available at: http://nanoracks.com/products/smallsat-deployment/ (last accessed January 30, 2016).

NASA. "Nanosatellite Launch Adapter System (NLAS)" (April 30, 2013): Available at: http://www.nasa.gov/centers/ames/engineering/projects/nlas.html#.Vqx19rIrIgs (last accessed January 30, 2016).

NASA. "CubeSat Data Analysis" (April, 2015): Available at: https://sma.nasa.gov/docs/default-source/News-Documents/cubesat-data-analysis.pdf?sfvrsn=0 (last accessed March 22, 2016).

Oppenheimer, P. M., Romano, M., Blocker, A. et al. (2008): Novel Three-Axis Attitude Control System for CubeSats with High Agility and Pointing Accuracy Requirements. *Advances in the Astronautical Sciences,* Vol. 133, pp.615-632.

Planet Labs. "Flock 1" (2015): Available at: https://www.planet.com/flock1/ (last accessed September 2, 2015).

Polat, H.C. (2016): *Prototype Design and Mission Analysis for a Small Satellite Exploiting Environmental Disturbances for Attitude Stabilization*, Space Systems Academic Group, Naval Postgraduate School, Monterey, CA.

Puig-Suari, J. (2008): The CubeSat: The Picosatellite Standard for Research and Education, presented at AIAA Space Conference & Exposition, San Diego, CA.

Sandau, R. et al. (2008): *Small Satellites for Earth Observation*, London, UK: Springer.

Spacecraft Robotics Laboratory (2016): Available at: http://my.nps.edu/web/srl/ (last accessed August 23, 2016).

Stickler, A. C. and Alfriend, K. T. (1976). Elementary Magnetic Attitude Control System. *J. of Spacecraft and Rockets*, Vol. 13(5), pp. 282–287.

Swartwout, M. "CubeSat Database" (2016): Available at: https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database (last accessed January 5, 2016).

Swartwout, M. (2010): A First One Hundred CubeSats: A Statistical Look. *JOSS*, Vol. 2 (2), pp. 213–233 (Available at www.jossonline.com).

Swartwout, M. (2011): Attack of the CubeSats: A Statistical Look, presented at 25th Ann. AIAA/USU Conf. on Small Satellites, Logan, UT, Paper SSC11-VI-04.

US Naval Academy (2014): USS Langley, presented at 2014 CubeSat Developers Workshop, San Luis Obispo, CA.

Virgili, J. and Roberts, P. C. (2013). ΔDsat, a QB50 CubeSat Mission to Study Rarefied-gas Drag Modelling. *Acta Astronautica*, Vol. 89, pp. 130–138.

Virgili-Llop, J. et al. (2016): Using Shifting Masses to Reject Aerodynamic Perturbations and to Maintain a Stable Attitude in Very Low Earth

Orbit, presented at the 26th AAS/AIAA Space Flight Mechanics Meeting, Napa, CA, February 14-18, Paper AAS16-354.

Votel, R. and Sinclair, D. (2012): Comparison of Control Moment Gyros and Reaction Wheels for Small Earth-observing Satellites, presented at the Ann. AIAA/USU Conf. on Small Satellites, Logan, UT, Paper SSC12-X-1.

White, J.S., Shigemoto, F.H., and Bourquin, K. (1961): Satellite Attitude Control Utilizing the Earth's Magnetic Field, NASA-TN D1068, Aug.

Wie, B. (2008): *Space Vehicle Dynamics and Control* (2nd ed.), AIAA Education Series.

Xiang, T., Meng, T., Wang, H. et al. (2012): Design and On-orbit Performance of the Attitude Determination and Control System for the ZDPS-1A pico-satellite. *Acta Astronautica*, Vol. 77, pp. 182–196.

Zwyssig, C., Baumgartner, T., and Kolar, J. W. (2014, May): High-speed Magnetically Levitated Reaction Wheel Demonstrator, in *Proc. 2014 Int. Power Electronics Conf.* (IPEC-Hiroshima 2014-ECCE ASIA), pp. 1707–1714, IEEE.