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On Structure and Secondary Linkages in Polymers Based on Glycidyl Azide Polymer and Diisocyanate

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ABSTRACT

Polymers based on glycidyl azide polymer (GAP) and isocyanate present molecular structures dependent on NCO/OH molar ratio and diisocyanate reactivity. In this study, GAP polymers are obtained from a reaction with aromatic (toluene diisocyanate, TDI) or aliphatic (isophoranediisocyanate, IPDI) diisocyanates, varying the NCO/OH molar ratio from equimolar to 2.5. The increment in NCO/OH molar ratio increases the gel fraction in GAP/TDI polymers up to 90 wt%, along with a progressive growth in their glass transition temperature (Tg), which rises 10 °C from NCO/OH equimolar to 2.5. In opposition, in the GAP/IPDI polymers, the maximum gel fraction is 20 wt%, and the Tg value practically does not change in NCO excess. Infrared spectroscopy shows the predominant presence of urethane groups in polymers containing up to 2.0 NCO/OH molar ratio; however, at 2.5, urethane and allophanate characteristic bands are present in both polymers. That reactivity is controlled by chemical kinetics since the activation barrier of the reaction between the GAP and TDI is 10 kcal.mol-1 lower than in the corresponding reaction with the IPDI. This difference results from the sum of the higher hyperconjugative interactions, approximately 65%, and the lower steric hindrance, about 35%, in the activated complex containing the TDI.

Keywords: Allophanate; GAP; Hiperconjugative interaction; Steric hindrance.

INTRODUCTION

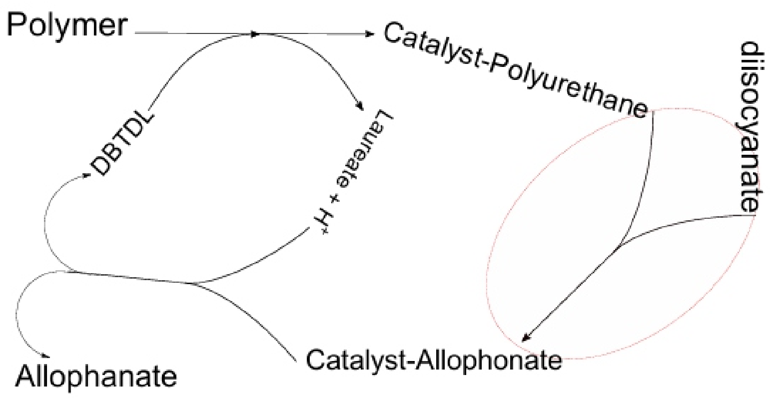
The glycidyl azide polymer (GAP) has been reported as an energetic binder in the literature for at least 30 years (Ampleman 1993; Beaupré et al. 2003; Frankel et al. 1988; Keicher et al. 2009; Lee et al. 2019. Min et al. 2014). GAP is a prepolymer with a molar mass varying from 1,500 g.mol-1 to 2,600 g.mol-1 (Frankel et al. 1992) and presents terminal secondary hydroxyl reactive groups and azide groups, which confer energetic character to this material.

In order to achieve a solid material with mechanical resistance, GAP prepolymer should react with a chain extensor. A conventional reaction that allows the increase in GAP molar mass is through the reaction between GAP terminal secondary hydroxyl group and di or tri isocyanates (Hagen et al. 2015; Kasıkçı et al. 2001; Keskin and Özkar 2001; Lee et al. 2019; Reshmi et al. 2015; Selim et al. 2000; Zhai et al. 2013), which is similar to that occurring among a polyol and diisocyanates, resulting in a polyurethane (PU).

The reaction between hydroxyl and isocyanate groups yields as a primary product a urethane group (Ionescu 2005; Szycher2012). Nonetheless, secondary reaction products have been reported in the literature. In particular, the formation of the allophanate group was described at NCO excess in the presence of a catalyst and temperatures around 50 °C (Ionescu 2005; Lapprand et al. 2005; Poljanšek et al. 2014; Reshmi et al. 2015; Sekkar et al. 2003). Lapprand et al. (2005) also cited the formation of heterocyclic isocyanurate in PU reactions at high NCO/OH ratios, elevated temperatures (~ 100 °C), and with a catalyst. The authors reported that the heterocyclic isocyanurate was the final product in these reaction conditions, while allophanate and urethane groups were detected only as intermediate reaction products.

Aromatic diisocyanates are more reactive than aliphatic ones due to the electron-withdrawing aryl group bonded to -NCO (Ionescu 2005). GAP polymer networking containing either toluene diisocyanate (TDI) or isophorane diisocyanate (IPDI) as curative agents has been reported in the literature (Eroglu and Guven 1998; Hagen et al. 2015; Manu et al. 2008, 2009; Min et al. 2014; Reshmi et al. 2015).

In the present study, polymers of GAP/TDI or GAP/IPDI were prepared using NCO/OH molar ratio varying from equimolar to NCO excess. Although energetic binders based on GAP and diisocyanates containing NCO excess do not yield propellant with adequate properties, this study aims to investigate the resulting polymer chemical structures and their dependence on NCO content and diisocyanate reactivity. An in silico experiment estimated the energies involved in the allophanate group formation in GAP/diisocyanate reactions at NCO excess. Sung et al. (2018) proposed that mechanisms for the reactions in which nucleophiles attack electrophilic centers as -NCO group have included steps like protonation/deprotonation, complex reactant-catalyst forming, regeneration of catalyst, and the formation of the N-C linkage (Fig. 1). In the present simulation, the focus was on evaluating the reactivity between urethane moieties from GAP/diisocyanate polymers and the -NCO functional group of aromatic (TDI) or aliphatic (IPDI) diisocyanate compounds, i.e., the N-C allophanate bond forming reaction step.



Source: Elaborated by the authors.

Figure 1. The proposed mechanism for the formation of allophanate compounds from PU and diisocyanate in excess NCO shows the investigated step highlighted by the dashed circle.

MATERIALS AND METHODS

GAP/diisocyanates polymers preparation

GAP was synthesized as described previously (Sciamareli et al. 2009) and the hydroxyl content (0.93 mmol·g-1) was determined by potentiometric titration. GAP molar mass was monitored using a gel permeation chromatography (GPC) Waters 1515, with tetrahydrofuran (THF) (1 mL·min-1) at 40 °C as eluent. Three µ-Styragel® columns (Waters HR 0.5, HR 1, HR 4) were used, with refractive index detector model 2414. The calibration was carried out with polybutadiene standards (Mn=57,700, Mn=29,600, Mn=13,300, Mn=5,750, Mn=2,860, and Mn=831). The GAP average molar mass (Mw) was 1,534 g.mol-1, and its polydispersity was 1.20. TDI 80/20 from Pronor Petroquímica, IPDI, and dibutyl tin dilaurate (DBTDL) from Cesbra Chemistry were used as received. GAP/diisocyanate polymers were prepared with different NCO/OH molar ratios (1.0; 1.5; 2.0; and 2.5). The catalyst used, DBTDL, was added at 1/250 DBTDL/GAP weight ratio. Before the addition of diisocyanates, GAP was maintained under vacuum at 65 °C for 12 hours to remove any traces of water. The GAP/diisocyanate mixtures were held under vacuum at 65 °C and 25 kPa for 7 days to allow a complete reaction between NCO and OH groups. The GAP polymers were named with the abbreviation of the monomers, GAP/TDI and GAP/IPDI, followed by the NCO/OH molar ratio, as shown in Table 1.

Table 1. GAP/diisocyanate polymers named according to NCO/OH molar ratio

NCO/OH molar ratio	Polymers	
1.0	GAP/TDI 1.0	GAP/IPDI 1.0
1.5	GAP/TDI 1.5	GAP/IPDI 1.5
2.0	GAP/TDI 2.0	GAP/IPDI 2.0
2.5	GAP/TDI 2.5	GAP/IPDI 2.5

Source: Elaborated by the authors.

Characterization

Glass transition temperature (Tg) and GAP/TDI polymers were evaluated by differential scanning calorimetry (DSC Q100, TA Instruments) under nitrogen flow (50 mL.min-1) in a temperature range from -90 to 150 °C at a heating rate of 20 °C·min-1. The results reported in this study correspond to the second heating scan. The Tg was calculated at half height. The fraction of gel was evaluated by swelling test in THF solvent in accordance with the literature (Chung et al. 2012). GAP/TDI polymers (0.4-0.5 g) were immersed in THF for 24 hours. The polymers were then filtrated, evaporated, and weighed.

The FT-IR spectra were performed using a PerkinElmer Spectrum One spectrometer (resolution 4 cm-1; gain 1; 20 scans, MIR spectral range 4000 cm-1 to 550 cm-1 in the reflection mode with universal attenuated total reflection [UATR] accessory). The UATR accessory allows infrared spectra to be directly obtained from liquid samples (row materials) or solid samples (GAP polymers) with no additional sample preparation.

In silico experiments

The unconstrained geometry optimizations have been carried out using the Firefly (Granovsky 2016;

Schmidt et al. 1993) package at the HF/STO-3G(d,p) level (Frisch et al. 1984; Hehre et al. 1969; Pietro et al. 1981) with an algorithm based on the quadratic approximation (QA) (Jensen 1995) and a threshold gradient value of 10-6a.u. Frequency analyses were conducted to verify the nature of the obtained stationary structures. Intrinsic reaction coordinate (IRC) calculations were performed by the Gonzalez-Schlegel second-order method (Gonzalez and Schlegel 1991) with the former threshold gradient value and a step size between points on the reaction path of 0.2 a.u. The hyperconjugative and steric exchange interaction energies were calculated according to natural bond orbital (NBO) analyses (Glendening et al. 2004). Structures, charts, and surfaces were drawn by the wxMacMolPlt and JMol software (Bode and Gordon 1998; Jmol 2004). The GAP/diisocyanate polymer models have three GAP monomers bonded to one diisocyanate compound (Fig. 2).

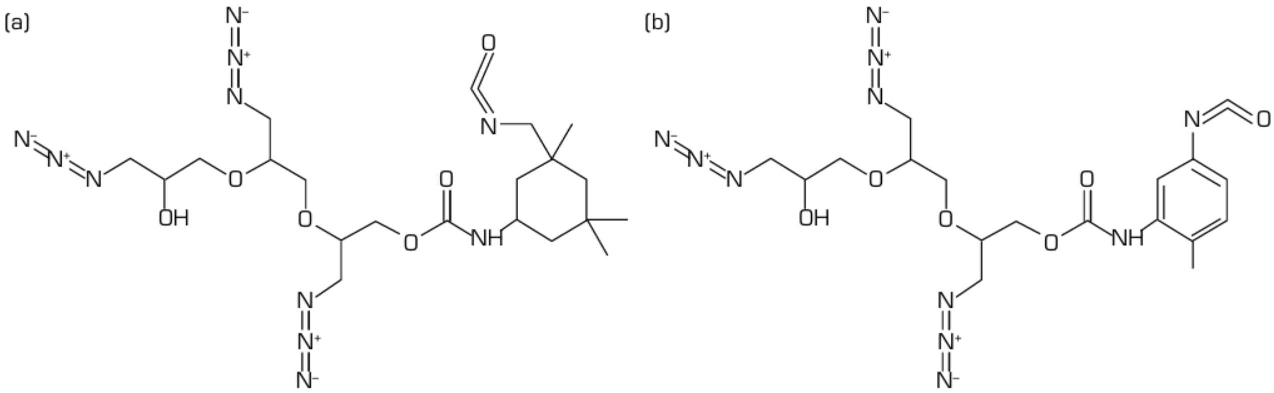


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Figure 2. 2D oligomer structures used as polymeric model in computational studies: a) GAP/IPDI; b) GAP/TDI.

RESULTS AND DISCUSSIONS

Physical characterization

The GAP/TDI and GAP/IPDI polymers showed physical characteristics dependent on both NCO/OH molar ratio and diisocyanate nature, aliphatic, or aromatic. The appearance of the GAP/diisocyanate polymers changed from a solid paste at an NCO/OH equimolar ratio to a flexible solid at 2.5 NCO/OH molar ratio. Nonetheless, GAP/TDI 2.5 was similar to an elastomer, while the respective GAP/IPDI polymer presented yielding under tension as a thermoplastic. These characteristics indicated morphological differences between the polymers resulting from the addition of excess TDI or IPDI, suggesting the formation of a crosslinked molecular structure in the GAP/TDI polymers and linear chains as the predominant molecular structures in the GAP/IPDI polymers.

Crosslinking in the GAP/diisocyanate polymers was investigated by analyzing their gel fraction, estimated by performing swelling tests in THF. The variation of the gel fraction as a function of the NCO/OH molar ratio is shown in Fig. 3. At NCO/OH molar ratios greater than 1.0 for GAP/TDI polymers (Fig. 3a), the gel fraction displayed a substantial increase, reaching 90 wt% at NCO/OH 2.5. On the other hand, GAP/IPDI polymers (Fig. 3b) showed practically no change in the gel fraction from the equimolar ratio until NCO/OH 2.0, and at NCO/OH 2.5, the gel fraction was approximately 20 wt%.

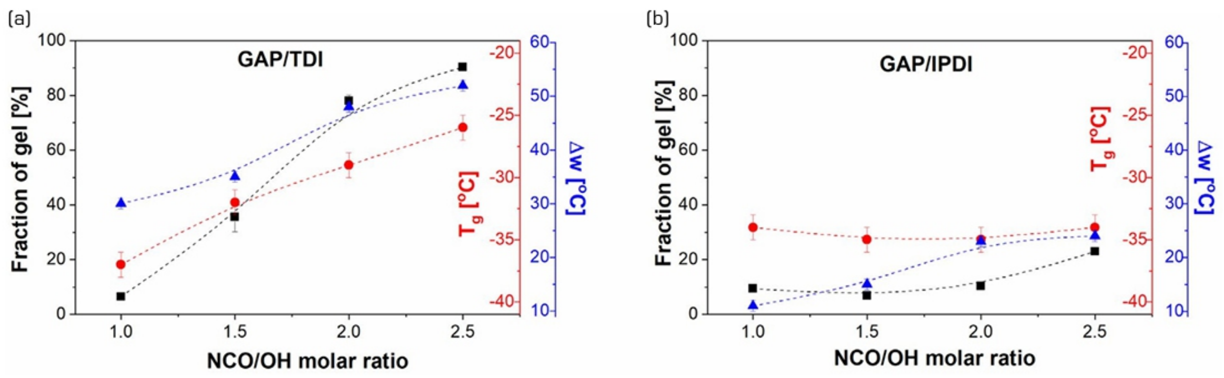

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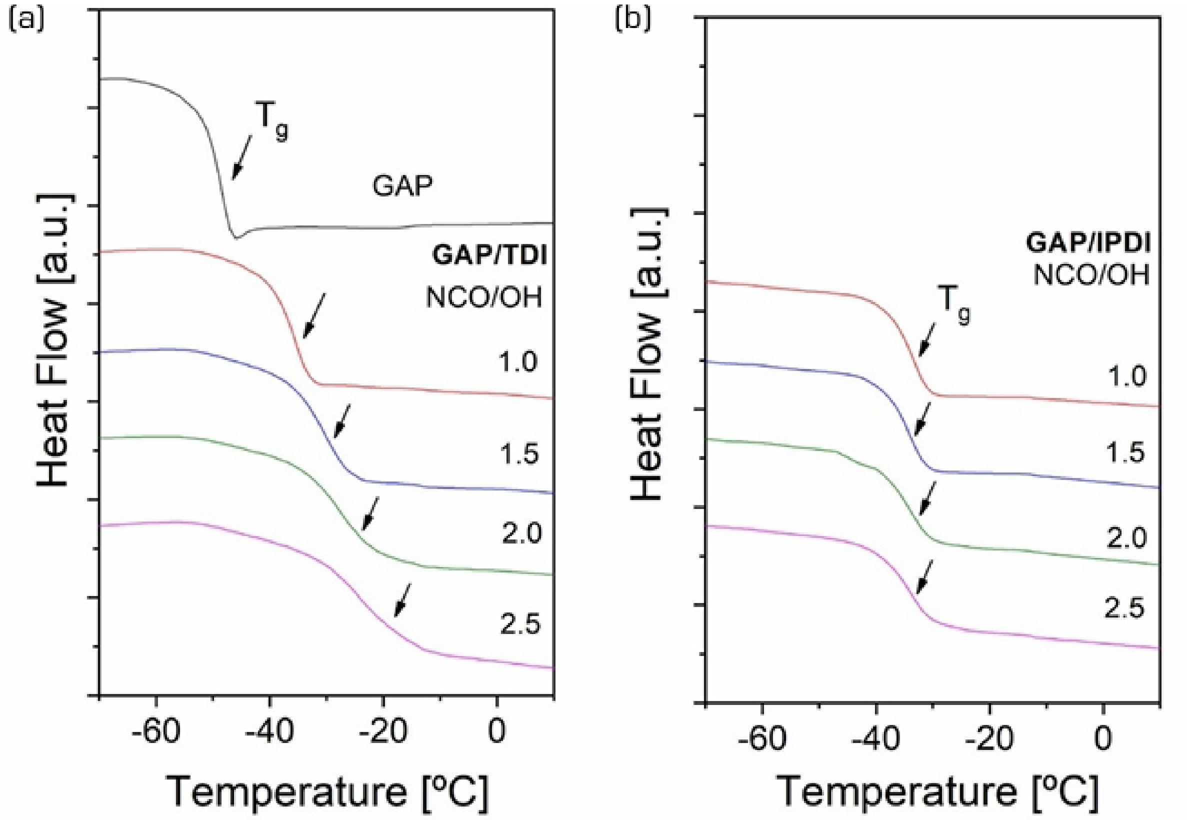
Figure 3. Physical properties of GAP/diisocyanate polymers: gel fraction [■]; Tg [●]; Tg width (Δw) [▲].

The glass transition of polymers was investigated by DSC. These analyses were performed in two heating cycles in the same temperature range. The first heating scan was used to monitor an eventual residual reaction between GAP and diisocyanates due to the experimental conditions used in the preparation of the polymers. However, no exothermic peak was detected during the first heating scan, and the Tg obtained in the first and the second heating coincided. Both results indicated that all reactions occurred during the preparation of the polymers.

Sekkar et al. (2003) compared the influence of NCO/OH molar ratio in PU based on hydroxyl-terminated polybutadiene (HTPB) with TDI or IPDI, varying from 1 to 1.5. The authors reported that the crosslink density of HTPB/TDI with NCO/OH molar ratio 1.5 was approximately 1.5 superior to that found for the respective PU obtained with IPDI, and the Tg values of HTPB/diisocyanate PU did not change with the increase in NCO/OH molar ratio.

In the present study, the gel fraction observed for GAP/TDI containing NCO/OH molar ratios 1.5 and 2.5 were approximately 3.5 and 4.5 higher than those observed for the respective GAP/IPDI polymers. The high gel fraction observed for GAP/TDI polymers was a consequence of the higher reactivity of the aromatic diisocyanate as compared to the aliphatic one, like in the PU system studied by Sekkar et al. (2003). Another important difference between GAP/diisocyanate and HTPB/diisocyanate polymers is the reactivity of HTPB, which possesses primary hydroxyl groups. In contrast, GAP has secondary hydroxyl groups with lower reactivity, which can explain the low fraction of gel observed for the GAP/IPDI polymers, even in higher excess of diisocyanate groups compared to that reported in the literature (Sekkar et al. 2003) in HTPB/IPDI polymers GAP/diisocyanate polymers showed a single glass transition in DSC curves (Fig. 4), which indicates no phase segregation during the GAP and diisocyanates reaction, resulting in a predominant chemical structure related to each polymer composition.

The GAP/TDI polymers presented a progressive increase in the Tg with the NCO/OH molar ratio increment (Fig. 3). This behavior follows the growth in the gel fraction, which agrees with a network formation in NCO excess in GAP/TDI polymers. The Tg increase as a function of the degree of crosslinking in PU was also reported by Sasaki et al. (1973). Additionally, in GAP/TDI polymers, a change in the glass transition profile was observed in DSC curves with the increment of the NCO/OH molar ratio, which resulted in a broadening of the glass transition region (Fig. 4a). This broadening is consistent with a network formation with different crosslink densities dependent on the NCO/OH molar ratio, analogous to the reported for thermosets (Chartoff et al. 2009).



Source: Elaborated by the authors.
Figure 4. DSC curves obtained for polymers with different NCO/OH molar ratios.

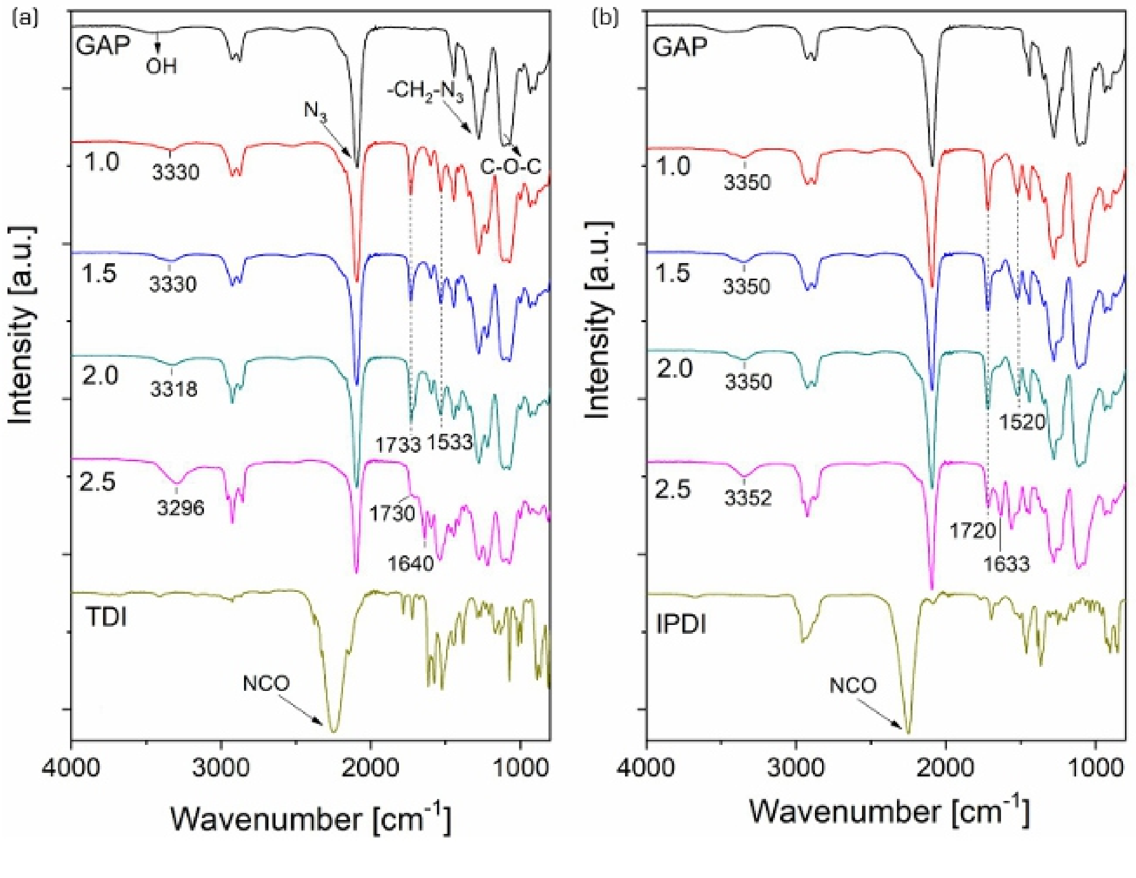
Manu et al. (2009) have studied GAP/TDI and GAP/IPDI polymers prepared in a mixture of 1,4-butanediol and 1,1,1-trimethylol propane as crosslinkers. They reported better mechanical properties for GAP/IPDI polymers, although the GAP/TDI polymer had a higher crosslink density. These authors attributed this behavior to the nature of the more homogeneous GAP/IPDI polymer containing mainly urethane linkages, which occurred because of the lesser extent of side reactions when compared with the more reactive aromatic diisocyanate. The authors also pointed out that many incomplete network linkages should be formed due to the side reactions in the GAP/TDI polymer.

In the present study, NCO/OH equimolar GAP/IPDI polymer presented the narrowest glass transition width (Fig. 4b), along with the low fraction of gel comparatively to the other GAP/TDI polymers (Fig. 3), which agrees with the majority presence of urethane linkage in the equimolar ratio. The higher the NCO/OH molar ratio in GAP/TDI polymers, the broader the glass transition width, which indicates the formation of a heterogeneous network due to the side reactions and suggests a partially crosslinked network, as reported in the literature (Manu et al. 2009). Considering the experimental condition of the GAP polymer preparation, the network junction should mainly contain allophanate groups formed in NCO excess (Ionescu 2005; Lapprand et al. 2005; Szycher2012).

Infrared spectroscopy

Infrared spectroscopy of GAP/diisocyanate polymers was performed to verify the chemical changes at different NCO/OH molar ratios. In PU, secondary linkages can occur depending on the experimental conditions, including the catalyst addition, NCO/OH molar ratio, reaction temperature, and time. As previously mentioned, in the NCO excess, the presence of a catalyst, and moderate temperature (50-60 °C), the allophanate group formation is expected as a secondary reaction product along with the urethane group.

The FT-IR/UATR spectra (Fig. 5) show the GAP polymers, pure GAP, and the respective diisocyanate reactants. The main bands in the spectrum of pure GAP are observed at 2090 cm-1 due to the stretching vibration of the N3 group and 1278 cm-1 assigned to -CH2-N3 absorption. The two bands at 1110 cm-1 and 1076 cm-1 are assigned to the ether group C-O-C vibration coupling (Frankel et al. 1992; Reshmi et al. 2015; Sciamareli et al. 2009; Wang et al. 2015). The GAP hydroxyl band is broadened, being observed between 3600 cm-1 and 3270 cm-1. The main absorption in TDI (Fig. 5a) is observed at 2250 cm-1, assigned to the stretching of the -NCO group (Manu et al. 2009; Reshmi et al. 2015; Smith 1979), along with characteristic aromatic bands at 1500 cm-1 and 800-700 cm-1 (Smith 1979). The NCO band in IPDI is observed at 2245 cm-1 (Fig. 5b).



Source: Elaborated by the authors.

Figure 5. FT-IR/UATR spectra of the GAP polymers (a) GAP/TDI and (b) GAP/IPDI.

The infrared spectra of GAP/diisocyanate polymers showed characteristic bands of the urethane groups for polymers obtained with NCO/OH molar ratio up to 2.0 (Fig. 5). In the literature, two absorptions have been reported in the carbonyl region for secondary urethane, one occurring between 1715-1735 cm-1(νC=O) and the other at 1530-1540 cm-1 (νC=O) (Smith 1979). GAP/ diisocyanate polymers containing up to 2.0 NCO/OH molar ratio showed carbonyl bands at 1733 cm-1 and 1533 cm-1 for GAP/TDI and bands at 1720 cm-1 and 1520 cm-1 for GAP/IPDI. In both GAP polymers, at 2.5 NCO/OH molar ratio, a spectral change occurred. However, in the GAP/TDI the spectral change was more pronounced, which can be attributed to the higher amount of allophanate group formed in this polymer. Kopusov and Zharkov (1966) reported the splitting of the vibrations of the C=O group in allophanate, which were reported to occur at 1736 cm-1 and 1695 cm-1 in ethyl α, γ-diphenylallophanate. Furukawa and Yokoyama (1979) reported bands at 1725 cm-1 and 1693 cm-1 for C=O stretching for 1,3-diphenyl isopropyl allophanate. In GAP/diisocyanate polymers, only one new band in the region of the carbonyl group was observed at 2.5 NCO/OH molar ratio, occurring at 1640 cm-1 and at 1633 cm-1 for GAP/TDI and GAP/IPDI polymers, respectively, which may be due to the overlap of the urethane and allophanate bands. Beyond the changes in the carbonyl region observed for GAP/TDI polymers, the N-H band(νN-H) was progressively shifted for lower wave number, from 3330 cm-1 to 3296 cm-1, suggesting that the higher the NCO content the higher the amount of hydrogen bonding present in this polymer (Fig. 5a). The hydrogen bonds are expected to involve the urethane -NH group as a proton donor and carbonyl or ether groups as hydrogen bond acceptors (Wolińska-Grabczyk et al. 2008). This result also points out the formation of an additional allophanate in GAP/TDI 2.5, which, along with urethane groups, may be responsible for the increase in the intensity of the -NH band.

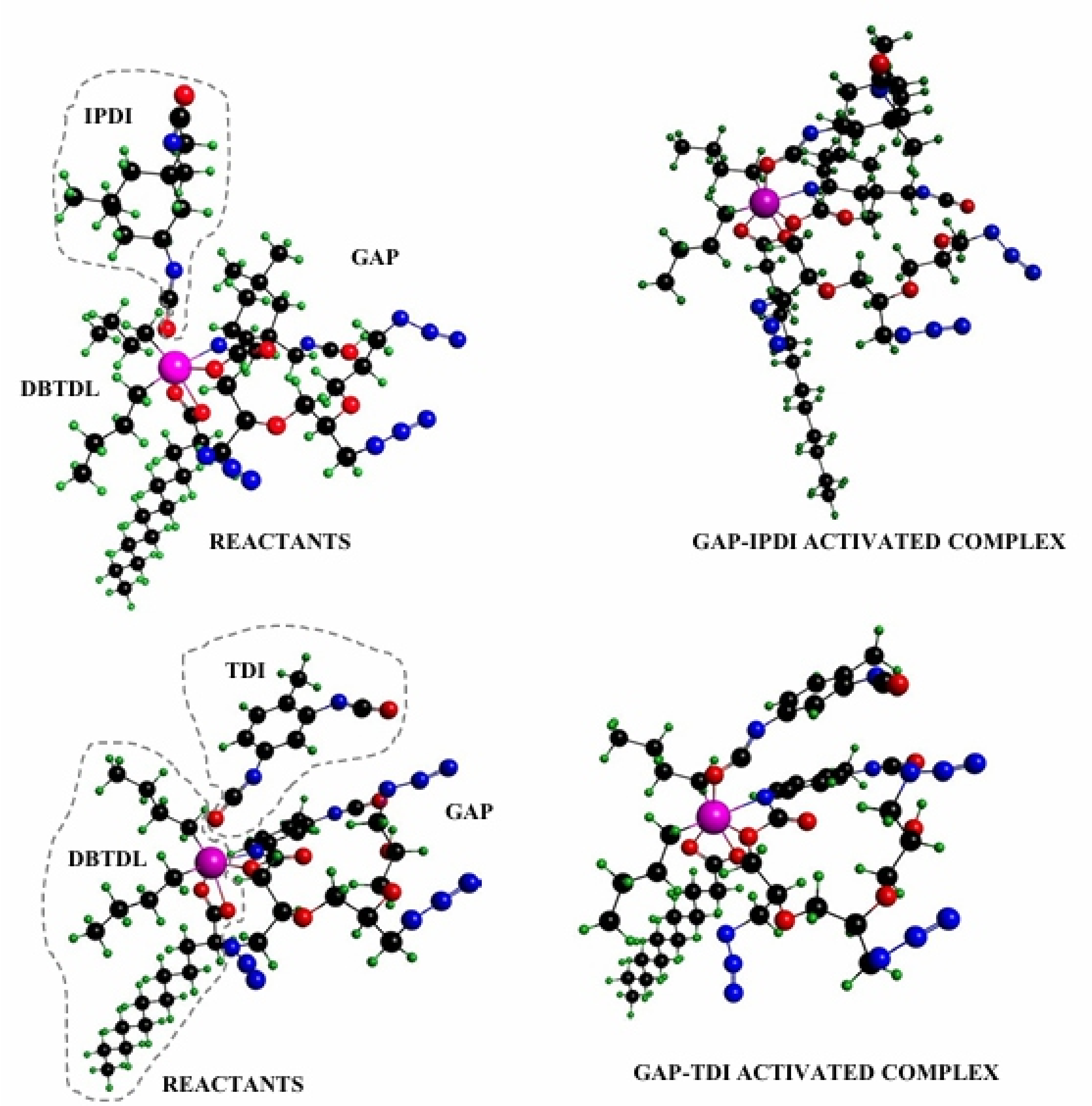
In GAP/IPDI polymers, the -NH band at 3350 cm-1 practically was not shifted with the NCO/OH molar ratio variation (Fig. 5b). Moreover, the change in the intensity of the N-H band (νN-H) was lower in polymers containing IPDI than that observed for GAP/TDI. This behavior agrees with the lower gel fraction obtained for these polymers, attributed to the low allophanate amount formed in the presence of aliphatic diisocyanate.

N-C allophanate quantum chemical simulations

In the present study, an in silico experiment was conducted considering the reaction energies between GAP polymers and diisocyanate excess. Minimum energy and transition states (TS) were identified, as shown in Fig. 6. The higher reactivity of the aromatic diisocyanate (TDI), as compared to the aliphatic one (IPDI), was attributed mainly to its kinetic stability since its transition structure showed a free energy of activation approximately 10 kcal.mol-1 lower than that of the activated complex with an excess of the aliphatic diisocyanate (Table 2 and Fig. 7). This lower kinetic reaction energy of TDI allowed its excess to react with the PU in the presence of the DBTDL catalyst at 60 °C, resulting in the formation of allophanate groups. The origin of lower reaction barrier heights in the TDI-catalyst-polymer reaction system may be due to stronger hyperconjugative interactions and lesser steric effects in its activated complex compared to the IPDI-transition structure.

The total energy of hyperconjugative interactions (Fig. 8) between the lone pair of urethanyl nitrogen atom (nNurethane) and unoccupied orbitals (n→π*; n→σ*) or lone pair of -NCO group (n→n) has accounted for nearly 65% of the energy difference of the activation barrier since they are about 6-7 kcal.mol-1 more stable in the TDI-activated complex according to NBO analyses (Table 3). Additionally, the steric hindrance has destabilized the IPDI-transition structure by approximately 3-4 kcal.mol-1 more than the respective TDI-activated complex (Table 4), corresponding to around 35% of the energy difference of the barrier content.

From the foregoing, hyperconjugative interactions and steric hindrance are major contributions to explaining the origin of the activation energies in reactions between GAP/diisocyanate polymers and excess of the diisocyanate, with the former making the main contribution to the reaction barrier height. Therefore, these in silico experiments agree with the experimental results, which indicated that the TDI excess may yield allophanate in a chemical reaction with GAP/TDI polymer catalyzed by DBTDL at 60 °C.



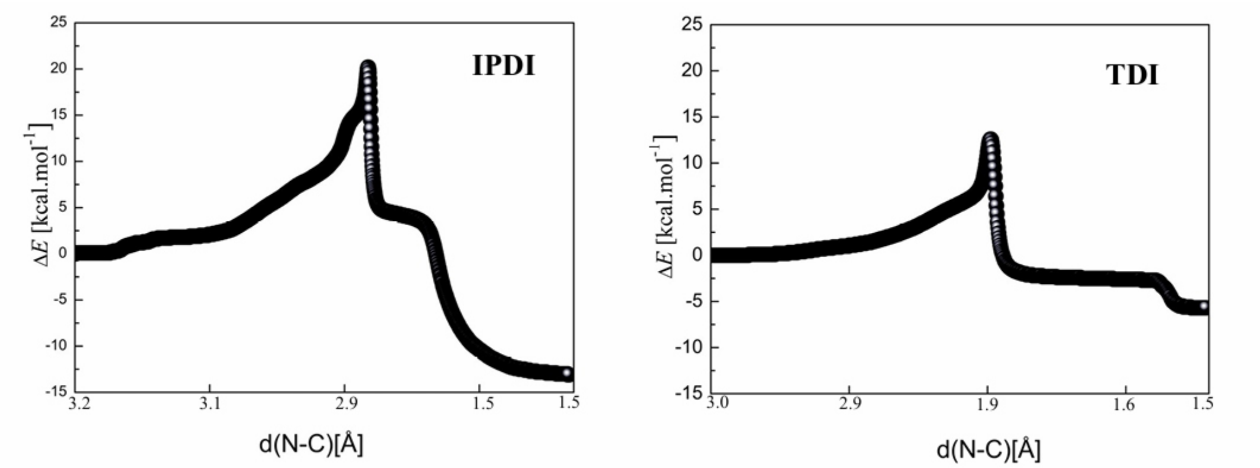
Source: Elaborated by the authors.

Figure 6. 3D structures of stationary states in the addition reactions of diisocyanate and urethane groups: carbon [●]; nitrogen[●]; oxygen [●]; hydrogen [●]; and tin [●].

Table 2. Activation parameters and interatomic distance in the rate-determining step investigated.

IPDI diisocyanate				
	$\Delta G^{\#}(60\ °C)^{a}$ [kcal.mol^{-1}]	$\Delta E^{\#}_{ZPE}{}^{b}$ [kcal.mol^{-1}]	$\Delta E^{\#c}$ [kcal.mol^{-1}]	d^{d} [Å]
Reactant	0.0	0.0	0.0	3.24
TS_{IPDI}	20.2	20.3	23.6	2.06
TDI diisocyanate				
	$\Delta G^{\#}(60\ °C)^{a}$ [kcal.mol^{-1}]	$\Delta E^{\#}_{ZPE}{}^{b}$ [kcal.mol^{-1}]	$\Delta E^{\#c}$ [kcal.mol^{-1}]	d^{d} [Å]
Reactant	0.0	0.0	0.0	2.99
TS_{TDI}	12.6	12.5	14.7	2.04

a: ΔG#(free energy of activation); b: ΔE# ZPE (electronic + zero point energy of activation); c: ΔE# (electronic energy of activation); d: d (interatomic distance Nurethane-Cdiisocyanate).
Source: Elaborated by the authors.

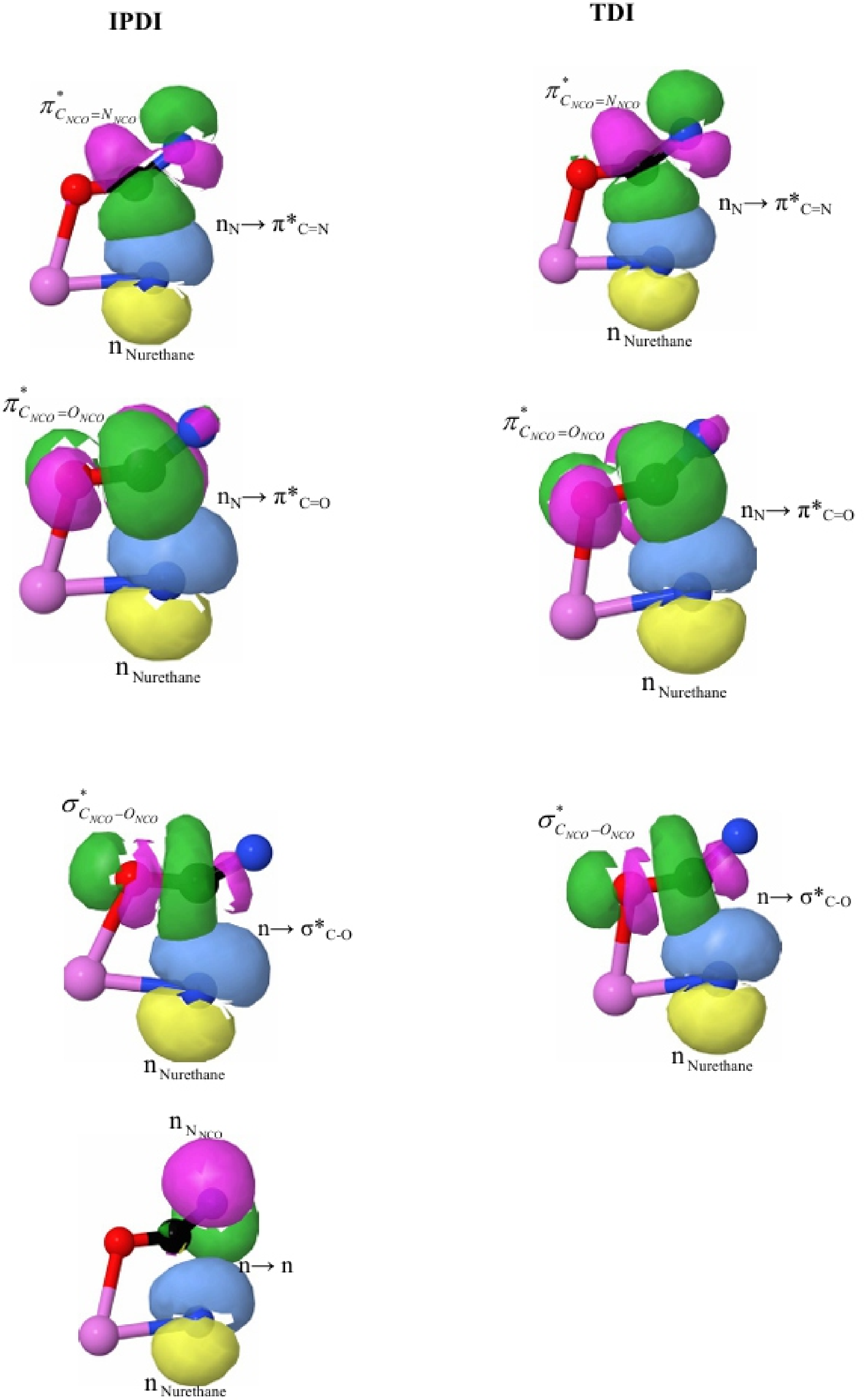


Source: Elaborated by the authors.
Figure 7. Energy versus bond length along the IRC for the allophanate group forming.

Table 3. Relative NBO hyperconjugative interaction energies (ΔEE2PRT) between NBO orbitals of activated complexes in the rate-determining step investigated.

Hyperconjugation	$\Delta E_{E2PRT}{}^{a}$ [kcal.mol^{-1}]
$n_{Nurethabe} \rightarrow \pi^{*}C_{NCO} = N_{NCO}$	-9.5
$n_{Nurethabe} \rightarrow \pi^{*}C_{NCO} = O_{NCO}$	0.8
$n_{Nurethabe} \rightarrow \sigma^{*}C_{NCO} - N_{NCO}$	-0.1
$n_{Nurethabe} \rightarrow N_{NCO}$	2.3
$\sum \Delta E_{E2PRT}{}^{a)}$	-6.5

a: ETSTDI- ETSIPDI. Source: Elaborated by the authors.



Source: Elaborated by the authors.

Figure 8. Hyperconjugative interactions between electron densities of the urethanyl nitrogen atom and of the diisocyanate groups for the activated complexes in forming allophanate. Isosurface values = 0.03 a.u.; carbon [●]; nitrogen [●]; oxygen [●]; and tin [●].

Table 4. Relative NBO steric exchange energies [ΔESteric] between minimum and transition structures in the rate-determining step investigated.

	$\Delta E_{Steric}{}^{a}$ [kcal.mol^{-1}]
IPDI	45.0
TDI	41.3
$\Delta\Delta E_{steric}{}^{b)}$	3.7

a: EstericTS- Esteric reactant; b: EstericIPDI- EstericTDI. Source: Elaborated by the authors.

CONCLUSIONS

In the present study, the reactivity of isocyanate showed the greatest influence on the polymer molecular structure. The GAP reaction with an excess of the more reactive aromatic diisocyanate resulted in the crosslinked network, and its gel fraction increases as the NCO/OH molar ratio increases, achieving 90% at 2.5 NCO/OH molar ratio. Moreover, in GAP/TDI polymers, the Tg increased approximately 10 °C with the NCO/OH molar ratio increment. This crosslinked structure was attributed mainly to the allophanate group yielded by the reaction of the urethane group from GAP/TDI polymers and -NCO group from excess of TDI. On the other hand, GAP polymers with aliphatic diisocyanate presented thermoplastic characteristics for all compositions studied. Although the allophanate group was detected by FT-IR in GAP/IPDI 2.5, its concentration was lower than that observed for the respective GAP/TDI polymer, as verified by the low gel fraction, even with NCO excess. The studies in silico have corroborated the experimental results. The kinetic parameters explained the high reactivity of TDI since its activation barrier is more stable than IPDI in about 10 kcal.mol-1. Those molecular modeling simulations showed that the electronic structure of the TDI-activated complex has higher hyperconjugative interactions and lower steric hindrance than the IPDI-transition structure, corresponding to 65 and 35%, respectively, of the difference in barrier height for the reaction between GAP/diisocyanate polymers and NCO.

AUTHOR'S CONTRIBUTION

Conceptualization: Dall'Agnol CB, Dutra RCL and Cassu SN; Formal Analysis: Dall'Agnol CB and Diniz MF; Funding Acquisition: Dutra RCL; Investigation: Dall'Agnol CB, Dutra RCL, Madureira LS and Cassu SN; Methodology: Dall'Agnol CB, Dutra RCL, Madureira LS and Cassu SN; Project Administration: Dall'Agnol CB, Dutra RCL and Cassu SN; Software: Madureira LS; Supervision: Dutra RCL and Cassu SN; Visualization: Dall'Agnol CB, Dutra RCL, Madureira LS and Cassu SN; Writing – Original Draft Preparation: Dall'Agnol CB, Dutra RCL, Madureira LS and Cassu SN; Writing – Review & Editing: Dutra RCL, Madureira LS and Cassu SN; Final approval: Cassu SN.

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Data will be available upon request.

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Strategy and Evaluation of Bilateral Agreement on Telemetry, Tracking, and Control Activities in Indonesia

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A B S T R A C T

India and Indonesia propose a bilateral cooperation to develop and operate telemetry, tracking, and control (TCC) ground stations to support satellite missions on geostationary orbits with the use of Geostationary Satellite Launch Vehicle (GSLV) since 1997, in order to master and commercialize space technology. This cooperation needs to be assessed in order to identify how it will a ect Indonesia and India and to establish an improvement strategy for improved business and ways to integrate. The objectives of this paper are to (i) evaluate the bene ts and cost of this cooperation, (ii) map the business model of the telemetry, and command ground station in Biak, and (iii) design a new strategy to get competitiveness. Descriptive analysis with canvas mapping and transaction cost perspective is the approach utilized. The article's results highlight that (i) Indonesia and India have mutual benefits from tangible and intangible side, (ii) Indonesia has a competitive advantage due to its geographic location and commercialization of Biak Ground Station, so its potential to Telemetry, Tracking, and Command (TT&C) commercial businesses in the future, not only to domestic, but also international market, and (iii) Indonesia needs collaborate with commercial entities and making optimum diplomation with G2B schema to get bene cially among parties to maximize TT&C infrastructure in Biak Island.

Keywords: Bilateral cooperation; Biak Ground Station; Indonesia; Evaluation; Strategy.

INTRODUCTION

India and Indonesia have bilateral cooperation, particularly in the eld of space. India is a developing country like Indonesia; it began with space activities in the 1960s but has since achieved technological mastery that now surpasses Indonesia in the eld of space technology. India has a space agency, the Indian Space Research Organization (ISRO), which has successfully conducted commercial rocket launches as well as a navigation satellite, the Indian Regional Navigation Satellite System (IRNSS), etc. Communication between space and ground segments is very crucial to the operating satellite and launch industry. Today, the technology and service telemetry and tracking (Telemetry, Tracking, and Command [TT&C]) market is rising and developing with constellation satellite issues. The position of technology at the ground station becomes important for the development of satellite technology and rocket launch technology, including for India and Indonesia themselves. According to Prasad and Pal(2003), TT&C systems provide the most critical telecommunication link between a satellite and ground station, providing the uplink for commands and the downlink for monitoring the various health parameters for the satellite's position in orbit. Lembaga Penerbangan dan Antariksa Nasional (LAPAN) operates ground stations in Rancabungur, Bogor, and Biak Island. More countries have bilateral agreements on the space sector, such as the operation of ground stations, to master and commercialize space technology. Since1997, India has proposed bilateral cooperation with Indonesia to build and operate TT&C ground stations to support satellite missions in geostationary orbits using the Geostationary Satellite Launch Vehicle (GSLV). On April 25, 1997, in Jakarta, LAPAN (the national space agency) and ISRO signed a Memorandum of Understanding between the National Institute of Aeronautics and Space of the Republic of Indonesia and the ISRO of the Republic of India for Cooperation in the Establishment of Telemetry, Tracking, Command Station for Satellites and Launch Vehicles as a precursor to the bilateral agreement between Indonesia and India in the eld of space technology (LAPAN 2019). e agreement marks the start of the construction of India's ISRO 1 and ISRO 2ground stations on Biak Island (Fig. 1). The main antenna's size is 10-11meters and transmits in the S and C bands.

Source: Elaborated by the author.

Figure 1. Biak Ground Station.

Since 1997, India has built two telemetry and tracking system (TT&C) stations on Biak Island. India also has ground stations in a number of countries, including Vietnam, Brunei Darussalam, and Indonesia. According to LAPAN (2019), there are provisions inthe 1997 agreement document and the updated MoU of 2018 regarding the transfer of ownership status to TT&C. e agreement has been modi fied and ends in 2019. ere have been few studies that show the benefits of such collaboration or cooperation during its 22-year implementation. The issue in this study is what motivates India to construct the TT&C ground station on Biak Island. What were the factors that contributed to the selection of the Biak Islands as a strategic location for TT&C? One of the competitive advantages in the eld of technology is the regional or geographic advantage (Zuhal 2010). e transfer of the TT&C ground station in Biak will be an interesting matter to see how competitive Indonesia will be in terms of technology mastery and commercialization activities. The bilateral cooperation agreement, which has a validity period, explains Indonesia's strategy in the face of potential global commercialization of the TT&C station business. Benchmark from a private actor, KSAT operators, a commercial satellite hub owned equally by

Kongsberg and the Department of Trade and Industry through Space Norway. KSAToperators operate ground stations in the Polar Regions, speci cally in the Arctic (Svalbard) and Antarctica, and they have contract business worth $43.8million. (Kongsberg 2017). is illustrates or example that TT&C is valuable for commercialization and pro tability in the supply chain for space technologies. How can the business possibility of the TT&C Biak Ground Station become something to do? is is demonstrated by the expanding ground station's role in assisting Indian space endeavors.

The purpose of this study is to (i) identify the bene t and cost of this cooperation, (ii) analyze Indonesia's potential for growth in terms of commercialization of Biak Ground Station, and (iii) develop a plan to gain a competitive advantage. The scope of the study is ex post policy analysis to evaluate bilateral agreements before 2019 and benchmarking with G2G and private practice in the TT&C program. According to Rainaldo (2017), the canvas business method is one suitable method for determining business potential. is method has the benefit of describing overall business conditions and is able to identify weaknesses and improvements that need to be made to increase competitiveness for future business planning (Herawati,2019; Solihah, 2014). It was used in this study to set a strategy for Indonesia in the future for operating TT&C ground stations.

METHODS

This research uses a mixed method of qualitative and quantitative analysis, including an overview of the literature, a costbene t analysis, and the canvas model. In the context of strategic management decision-making, business design evaluation, and cost-bene t analysis, the canvas model and transaction cost perspective are utilized. ere is both primary and secondary data in this study. Primary data was acquired through meetings, interviews, surveys, and focus group discussions (FGD) that were used to gather information. Secondary data is gathered from books, articles, publications, and other secondary sources. TT&C's business model can be mapped using a canvas model. In this model, an organization's business model is broken down into nine interconnected components, including customer value proposition segments, customer relationships, channels, key resources, key activities, partners, costs, and revenues. According to Osterwalder and Pigneur's (2010) model canvas, business models are de ned as "the rationale of how an organization creates, delivers, and captures value." Although employing it might assist users in balancing gain and goal to promote greater sustainability to make the canvas model, the identi cation stage of transaction costs during the operation of this TT&C ground station becomes important. Transaction cost is understood as an alternative mode of organizing transactions (governance structures, i.e., markets, bureaus) that minimize transactions (Williamson 1979). De ningtransaction costs based on Furubotn and Richert (2000) are costs for using the market (market transaction cost) and the cost of exercising the right to give orders within the company (managerial transaction cost). From identi cation transaction cost, it can be measure to cost-bene t to space program, like co-operation. Cost-bene t analysis is a tool to assist in decision making or the use of space technology (Hein etal. 1976; Hockley 2014). Transaction cost its uses to identify all cost and bene t include management cost (lobby, etc.) and operational cost during implementation partnership. In the economic institutional, is very useful to explain to social cost at least in governmental.

ANALYSIS

Scope of LAPAN-ISRO cooperation

International collaboration is one method for mastering space technology. The Indonesia Space Act is regulated in a special article on the implementation of commercialization through international cooperation. e items of cooperation arranged between the LAPAN and ISRO are included (LAPAN

2019): (i) space science, space exploration, use of space technology, monitoring the earth's environment from space and remote sensing of the earth; (ii) develop forms of multidisciplinary cooperation in the practical use of space technology and use the spin-o bene ts of space technology; (iii) operation, maintenance, addition, improvement, and use of the Integrated Biak TT&C Ground station for the mutual bene t of both parties; (iv) joint research and development activities in the eld of space technology; (v) exchange of technical and scienti c personnel appointed to participate in cooperation programs; (vi) organizing training, workshops, and seminar programs in areas of mutual interest, etc. TT&C is a program of bilateral cooperation between LAPAN and ISRO and has run for at least 22 years. is relationship of cooperation is highly bene cial to both parties.

Impact

The bilateral cooperation between LAPAN and India in the operation of the TT&C Biak 1 and 2 Ground Stations has an impact on both parties in terms of bene t and cost.

Indonesia

LAPAN (2019) mentions the following bene ts to Indonesia:

- Transfer of knowledge in data utilization and operation of the Biak TT&C Ground Station;
- Transfer of ownership and further use of the integrated Earth TT&C Biak Station;
- Launching of two satellites owned by LAPAN by Indian launchers at a cost of return (in kind);
- Capacity building in the mastery of space technology in elds including:

– Radio frequency (RF);
– Safety features, construction, control of movement of ground station (GS);
– Networking coordination GS to GS;
– GS trouble shooting soware engineering in data and interactive;
– Installation of redundancy power by ups and battery switch hold; and
– Installation of lightning system.

Bene ts and costs are divided into tangible and intangible values. In Table 1, it can be shown that the is greater than benefit from the tangible side. It is related to the business process of this cooperation that there is no revenue or tari as income. Besidesthat, Indonesia has bigger direct and indirect intangible bene ts that are not included in the state revenue component (Table1). Tosupport this, LAPAN must prepare a unit and teams to support this ground station. e direct bene t of this cooperation is that LAPAN can monitor (command and track) the satellite itself and got indirect bene ts, such as capacity building, training, and others.

Table 1. Estimation intangible and tangible bene t cost for Indonesia.

Tangible revenue ($)	Tangible cost ($)
TT&C service 20.000,	Operational 25.600,
Sum	Sum
Total R-C	(5.600)
Intangible benefit	Intangible cost
Capacity building Support satellite LAPAN A2, at S band Freq Satellite piggy back (launching cost)	AIS Data

Source: Elaborated by the authors.

India

The bene ts of operating the TT&C Biak Ground Station directly are for satellite monitoring activities owned and launched by India. India has one of the largest constellations of remote sensing satellites in the world today and needs support with the Indian Data Relay Satellite System (IDRS) (PraveenReddy etal. 2018). The beginning of the TT&C Biak 1 operation, according to Tanoemihardja etal. (2002), was operated to monitor the launch of PSLV and GSLV that were launching sites in Shriharikota.

It was con rmed by interviews with operator sta during a visit to the Biak TT&C, where the Biak TT&C has the function to support the IDRS to provide tracking and data acquisition support for all types, including supporting the launch and reception of remote sensing and telecommunications satellite TT&C data. TC Biak is known to track 23 satellites. Some of the satellites monitored are located in Low Earth Orbit (LEO) via geostationary relays, according to Praveen Reddy etal. (2018), namely Cartosat1, SARAL 2, Resourcesat, Cartosat 2, and Oceansat. Biak has an important value among the four ground stations that India has, which, according to Kasturiranjan (2001) in "Competition Science Vision", telemetry con rmation had been received from Biak Ground Station that the spacecra all systems were functioning well (Table 2).

Table 2. Estimation revenue and cost TT&C Biak Ground Station for ISRO/tear.

Revenue ($)	Cost ($)
TT&C service: uplink 1.200.000 Downlink 9.600.000	Operational and maintenance: (141.866)
Sum 10.800.000	Sum (141.866)
Benefit	10.658.133

Source: Elaborated by the authors.

The calculation in Table 2 is based on using a pessimistic scenario of the bene ts or bene ts obtained by the ISRO of 159.777 billion/ years in Rupiah or equivalent with 10.658.133 in Dollar (assume 1 $ = Rp. 15.000,) from the potential commercialization of Biak TT&C. Potential of commercialization Biak Ground Station From the perspective of the foreign developing situation, commercial TT&C is the trend of the times (Xu etal. 2018). With canvas mapping, the potential for commercialization of the operation of the TT&C Biak managed by LAPAN itself is revenue from the state at a minimum of 159,872 billion Rupiah, with segmentation of users spread from within and outside the country. AWS (2019) said that customer must buy or lease ground antennas to communication with satellite, must build business rules, and work ows to organize, structure, and route the data to employees or customers before it can be used to deliver data. erefore, it need signi cant capital investment and operational cost to build. e market price for (X Band-S Band) antennas is about $ 200 to $ 400 per pass, and trend to future will seek to o er lower prices to create a competitive advantage (Henry 2017). potential of the future TT&C Biak in the canvas model is mapping as Fig. 1.The business

According to Hasbi (2019) in Forum Group Discussion for commercialization space issues, the push demand or commercialization of equatorial TT&C ground station services on Biak Island are:

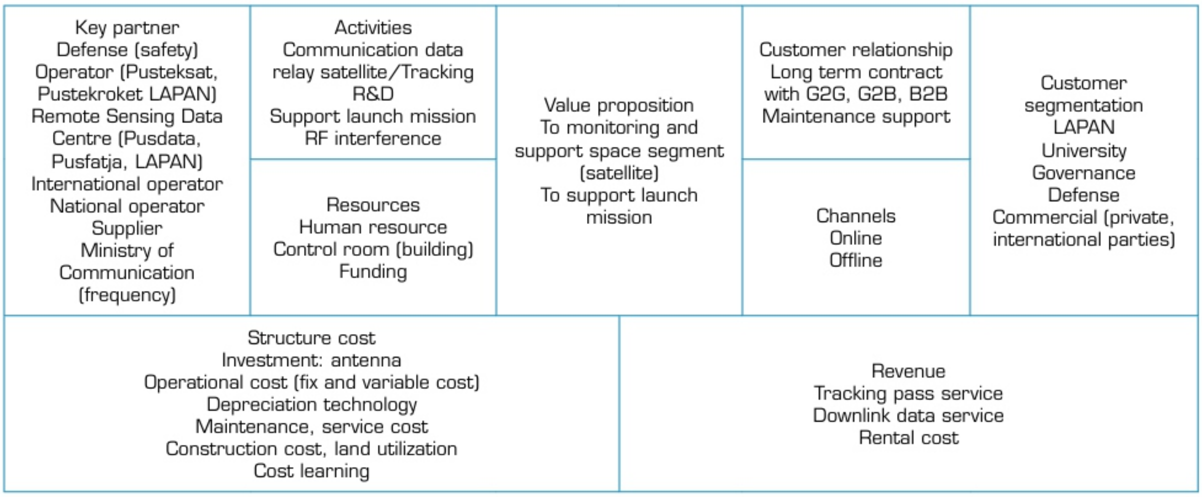
• Supporting the low orbit satellite constellation program;
• Supporting the spaceport on Biak Island;
• Supporting the most recent TT&C ground station in Bogor;

• e availability of ISRO's satellite control facility, which has a strategic position on Biak Island;
• Establishing a partnership with the commercialization industry entity for the development of the ground station;
• Increasing demand for low-orbit satellite launches, which will require ground stations for operations.

To get bene ts of cooperation, from institutional economic, identify transaction cost is needs to be included in the term bilateral cooperation. There are need to be arrange xed and variable transaction costs that maybe arise from the cooperation in the certain period time, and both in terms of revenue and costs. To achieve and develop TT&C market, there are need identify several cost includes search and information cost, supervision, managerial, and political cost. There are very important to get cooperation and optimum negotiation. e low cost of political costs and managerial that there are re ect transaction costs may a ect to performance of not optimally their functions of organization (Perwitasari 2019a). To joint in international commercial TT&C market, Indonesia must learn from existing G2G practices and private industry. India is a partner and potential user to this.

Figure 2 show scenario of business model of TT&C Biak before LAPAN merger into BRIN (Badan Riset dan Inovasi Nasional). is mapping is based on discussion and in-depth interviews with keyperson. LAPAN has mandatory from Space Act Number 23 Year 2013 to build commercial space activity, including ground segment. Biak Ground Station 1 and 2 will be Indonesia asset, so there are huge potential to develop. India and or other space entities maybe joint on this business model with Business of Business (B2B), Government-to-Government (G2G), or Business to Government (B2G). The customer or user of TT&C market are domestic and international. e operational of ground station will be on online and o ine format. The utilization and spin o satellite technology on Indonesia and satellite will be launch (small satellite) and commercial spaceport in Biak is high value proportion. According Perwitasari (2019a), the rst determination Biak selected to spaceport based technical criteria (location, safety, security) and its need support a TT&C service from Indonesia ground station. LAPAN needs partners likes India and other potential players in the satellite communication industry to share space capacity of ground station to get pro t and scale economies.

Since 2021, LAPAN mergers into BRIN and this canvas model was change. e transformation organization with BRIN structure has consequence with business model (canvas mapping). Under BRIN structure, space infrastructure facilities including TT&C ground segment is operated under Deputy of Infrastructure, Research and Innovation (DIRI). Research Organization for Space and Aeronautics (ORPA) concerns with research and space activity. Key partner (actor) were changing, they are DIRI, ORPA, DFRI, Sestama, and others. This has consequent on space e-government in Indonesia. Structure organization was change and still progress until now.



Source: Elaborated by the authors.

Figure 2. Business canvas model of TT&C Biak by LAPAN (consent before merger into BRIN).

Strategy to create competiveness advantage

Prasad and Pal (2003), said that development, testing, and fabrication of these systems are quite involved, tricky and difficult, and required a lot of expertise to develop it. Miau and Holdaway (2000) mention that for country who lag behind in space technology but want to build up their capacity to develop their own space in the future, the fastest way is to take advantage of the opportunity when procuring ground system from firm advanced country by requiring technology transfer.

Therefore, by looking at the business potential of mapping the canvas model, the strategy that must be carried out by LAPAN (now BRIN) by looking at the benefits of commercialization of TT&C Biak for India and the benefits is not optimum for Indonesia during the collaboration. Several strategies according the information obtained from the FGD discussion results and interview are:

• Evaluating existing bilateral co-operation ;

• Supporting technical aspect needs to operation of spaceport in Biak (Perwitasari 2019), with competitiveness of TT&C Biak with commercial schemes going forward by paying attention to safety and security aspects;

• Promoting local industry to support and join in TT&C business and research and development in the long term.Countries or international partners are very interested in the excellence of the Biak region as a competitive advantage.

Theposition of Biak is strategic for Indonesia as well as space faring nations. is is one of the reasons Indonesia's geographical location bene ts from the growth of ground-segment enterprises through the commercialization of TT&C. A number of nations use the bilateral agreement as the centerpiece of their e orts to commercialize space, particularly with regard to the operation of spaceports.

In order to take advantage of the chances for involvement and collaboration provided by the partnership, Perwitasari (2019b) argues that national coordination is necessary, involving academia, business, and government or triple helix network. Due tothe absence of numerous parties in this ISRO-LAPAN cooperation in the TT&C operation in Biak, the benefits are only felt by thetwo parties involved, with India reaping the majority of the benefit. In order to maximize benefits between India, BRIN, and other national stakeholders, BRIN must build a co mmercial model incorporating industry and other players from the opportunity of partners in the canvas model discussed above. Indonesia currently has an SBSN initiative that will create TT&C and launch a commercial business landscape. Construction was completed in 2022, with an anticipated opening in 2023.

CONCLUSION

In global or regional cooperation, bilateral cooperation is a part or method of the space collaboration strategy. Due to the global space value chain, an evaluation of international partnerships is required to accelerate space technological mastery. Usingex-post institutional economic evaluation and learning from current practice from international can be used to see input, activities, and impacts from bilateral activities, especially TT&C between Indonesia and India. Indonesia and India have mutual bene ts. Indonesia have tangible and intangible bene ts like piggyback satellite (on the launch of its own satellite experiments, such as LAPAN A1, LAPAN A2, and LAPAN A3 and next A4) and capability building for TT&C scienti c research, etc. According to CBA analysis, India has bigger bene t, because they have mature commercial industry for example spaceport, satellite and use support TT&C from Biak. India can monitor and communicate with its satellite and the space industry and operations have a signi cant economic impact (multiplier e ect).

Indonesia is still progress to build space industry especially promoting private local actor on TT&C program. Indonesia has a competitive advantage due to its geographic location and the operation of the Biak Ground Station for both domestic and foreign users. A crucial piece of technology for the Biak spaceport's functioning is the TT&C Biak Ground Station. In order to get scale economies, bilateral cooperation with new model businesses is being evaluated. In order to develop an e cient space business and use o set to obtain technology transfer based on the canvas model, Indonesia needs collaborate with commercial entities and making optimum diplomation with G2G, G2B schema to get bene cially among parties.
Because the limitation in this evaluation research did until 2019, from this conclusion, there is need next research to ongoing evaluate bilateral agreement with new space government structure in Indonesia.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Intan P; Validation Data: Intan P; Methodology and Analysis: Intan P and Firmansyah; Writing: Intan P and Firmansyah; Investigation & data curation: Intan P; Review and editing: Intan and Firmansyah; Final approval: Intan P.

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Data sharing is not applicable.

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Robust Finite-Time Control for Guidance Law with Uncertainties in Missile Dynamics

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A B S T R A C T

In this paper, the robust nite-time control for impact angle guidance of missile dynamic system with uncertainties is investigated by combining linear extended state observer (LESO) and adaptive non-singular fast terminal sliding mode method. Speciallyfor dealing with existing uncertainties including time-varying parametric perturbation and nonparametric disturbances in high order line-of-sight rates and target acceleration, a robust LESO strategy is proposed for designing sliding mode-based impact angle guidance, which can guarantee that estimation error converges to the neighborhood of the origin in nite-time. Based on the proposed LESO framework, an adaptive non-singular fast terminal sliding mode guidance law is considered for realizing interception of maneuvering targets, which can guarantee asymptotically stability of the system. Simulation results are shown for con rming e ectiveness of the proposed guidance strategy of this paper. Compared with former methods, accuracy of estimation is increased by nearly two times, and miss distance is reduced by nearly two times.

Keywords: Terminal guidance; Targets; Angle of attack; Missile control.

INTRODUCTION

Guidance law of missile plays an important role in intercepting targets. e performance of missile can be further re ned when it can be insensitive and robust to target maneuvers and environmental disturbances. The well-known guidance laws design methods, line-of-sight (LOS) guidance, and proportional navigation guidance are widely employed due to their highly e cient and simple for practical applications (Lin etal. 1991). By utilizing proportional to the LOS angle rate to track targets in terminal phase, these approaches can e ectively realize asymptotic or exponential stability against constant velocity targets (nonmaneuvering targets) (Hou and Duan 2008; Ma etal. 2009). When dealing with cases where objects consist of uncertain maneuvers and disturbances of missile dynamics systems, the performances of the mentioned methods are limited. Therefore, robustness of engagement performance considering the uncertainties of the missile dynamics system is of importance for enhancing engagement performance during homing phase.

In the past decades, in order to improve robustness of engagement performance of guidance laws, many advanced control techniques have been considered, such as nonlinear H control terminal guidance law (Guo and Zhou 2009), optimal guidance law (Zhang etal. 2014), xed-time tracking control (Cui etal. 2023), and nite-time convergence guidance law (Zhou etal. 2009, 2016). In practical engineering, the controlled systems are usually required to reach steady response from transient response quickly. In theory, the control schemes in the sense of innity-time stabilization do not meet that requirement, since they usually lead to a long transient response of the closed-loop systems. In fact, the problem of finiteadaptive fault-tolerant control scheme is researched for a class of nonlinear systems with unmodeled dynamics, where the dynamic system is switched.

However, considering the advantages of fast response, insensitivity to parameter changes and disturbances, and no need for online system identi cation, sliding mode control (SMC) has broad prospects in practical missile interception targets. SMC (also known as variable structure control) is achieved by switching functions, switching the structure of the controller based on the degree to which the system state deviates from the sliding mode, thereby enabling the system to operate according to the prescribed laws of the sliding mode. e important advantage of SMC is robustness. SMC-based impact angle guidance law design is promising, achieving many insightful results (Lee etal. 2013). Considering head-on, tail-chase, and head pursuit engagements, SMC-based guidance laws is proposed, which can impose a predetermined interception angle relative to target's ight path angle in Tal (2007, 2011). An impact angle constrained guidance law based on SMC and linearization method is proposed to intercept stationary or slowly moving targets in Zhang etal. (2014). By combining power reaching law and exponential reaching law, a fast power reaching law is designed, reducing chattering of sliding mode and improving reaching speed (Zhou etal. 2009). Inaddition, by combining with other advanced control technique, integrated SMC-based strategies are also studied, such as fuzzy variable structure (Li etal. 2011) and radial basis function (RBF) neural network sliding mode variable structure (Wang etal. 2016). ese methods increase the complexity of controller undoubtedly while suppressing system chattering. Liu etal. (2016) and Zhang etal. (2013) improved the sliding surface and the approach law, respectively, both of which achieved some results in suppressing system chattering. However, the above methods cannot guarantee nite-time convergent performance, and consist of symbol function term in controller.

As for dealing with the existing disturbances of missile dynamics, there are two main directions. One idea is that disturbances are regarded as the unknown parameter of system. For these cases, adaptive control is e ective method, for example, in Cai and Xiang (2017) and Cai etal. (2017); adaptive nite-time controller and adaptive laws is constructed by adding a power integrator technique, and the stability of the corresponding closed-loop system is proved based on the nite-time Lyapunov theory. eother idea lies in estimating disturbances knowledge of maneuvering targets, using disturbance observer, Kalman lter techniques (Arasaratnam and Haykin 2009; Kandepu etal. 2008) technique.
In terms of the Kalman lter technique, its calculation process is complicated and algorithm is dependent on models of systems. If the proposed target model cannot match the actual motion, it may lead to divergence of lter, even failures on target tracking. In practical systems, the state variables are usually unmeasurable or just partly measurable, and some control plans may not be well implemented.

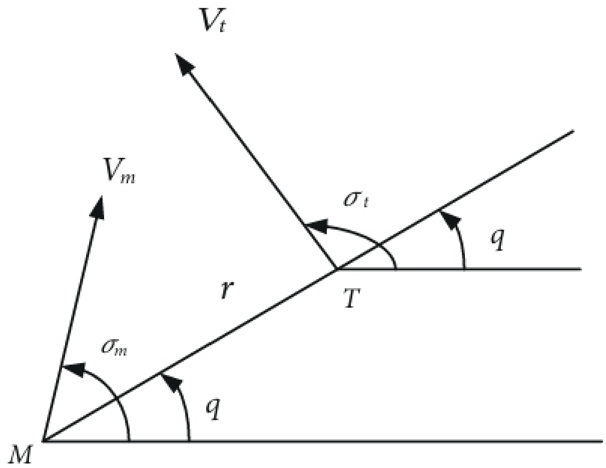
The observer can estimate those unmeasurable state variables; it overcomes the di culties caused by lack of accurate state information (Han 1995; Yao and Wang 2009). By using observer method, in Wang and Su (2013), a LESO is constructed using a linear function, meanwhile detailed selection procedure of the proposed LESO related parameters is given. In Fu etal. (2023), Ju etal. (2023), and Shao and Wang (2015), estimation error of the observer is proved to be bounded under unknown system conditions, and the quantitative relationship between observation error and expansion order is given. As for nite-time estimation of LESO, in Yang etal. (2015) and Yu etal. (2005), the relationship between observer parameters, speed error convergence, and steady-state error is considered. Moreover, the su cient conditions and related proofs to ensure the boundedness of the observation error are given, which provides a theoretical basis for the design of observer parameters.

From the aforementioned analyses, to e ectively estimate disturbances caused by maneuvering target and missile dynamic system for simplifying calculation process and realize nite-time convergence while suppressing chattering are important for intercepting targets. erefore, in this paper, the LESO-based terminal nite-time SMC method is proposed to design an adaptive nite-time guidance law for impact angle of missile. The proposed guidance law can reduce dificulties of calculation in estimating uncertainties and improve tracking performance for maneuvering targets in nite-time.
The rest paper is organized as follows. In the next section, the missile-target relative motion model is introduced. Main results of this paper, including uncertainties estimation based on LESO method, terminal SMC-based guidance law, are developed in Main results section. Then, for con rming e ectiveness of the proposed method, simulation results and comparison results are given, showing that the proposed method can improve high-precision guidance of missile. Finally, the conclusion of this paper is summarized in Conclusion section.

MISSILE-TARGET RELATIVE MOTION MODELING

Relative movement relationship between the missile and the target is introduced as shown in Fig. 1. The missile and the target are regarded as particles and are represented by M and T, respectively. In order to simplify the pursuit situation, it is assumed that the missile and the target are point masses moving in plane. According to the missile-target geometric diagram in Fig.1, motion equations of the missile-intercepting target can be obtained as follows (Eq. 1):

$$\begin{cases} \dot{r} = V_t \cos(q-\sigma_t) - V_m \cos(q-\sigma_m) \\ r\dot{q} = -V_t \sin(q-\sigma_t) + V_m \sin(q-\sigma_m) \end{cases} \tag{1}$$



Source: Elaborated by the authors.
Figure 1. Guidance geometry for missile-target engagement.

where r˙ is the relative distance between missile and target, r˙ is the derivative of r with respect to time, Vt , Vm, q, q˙ , t , and m are target rate, missile rate, line of sight angle, line of sight rate, speed direction angle of target, and missile, respectively.

Denoting the derivation of the relative motion states r and q as VR and Vq (the relative speeds of the missile and the target in the line of sight and vertical line of sight), respectively, the transformation is shown in Eq. 2.

$$\begin{cases} V_R = \dot{r} \\ V_q = r\dot{q} \end{cases} \quad (2)$$

Diferentiating Eq. 2 with respect to time, obtain Eq. 3:

$$\dot{V}_q = -\frac{V_R V_q}{r} + \omega - u + \varepsilon \quad (3)$$

where and u are the components of the target and missile acceleration in the LOS method, respectively, represents bounded uncertainties, including the unmodeled high-order part of the missile-target engagement model and disturbances of missile dynamic system.

By substituting Eq. 2 into Eq. 3, the model of missile-target relative movement can be derived as follow:

$$\ddot{q} = -\frac{2\dot{r}}{r}\dot{q} + \frac{1}{r}(\omega - u) + \frac{1}{r}\varepsilon \quad (4)$$

Based on extended state observer theory, the appearing uncertainties is extended to be a new state. Let $x_1 = \dot{q}, x_2 = -\frac{1}{r}(2\dot{r}\dot{q} - \omega - \varepsilon),$ combining the extended state with Eq. 4, the whole state expression of the missile-target model is described as follows (Eq. 5):

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + B_1\eta(t) \\ y(t) &= Cx(t) \end{aligned} \quad (5)$$

where $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} -\frac{1}{r} & 0 \end{bmatrix}^T$, $C = \begin{bmatrix} 1 & 0 \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 & 1 \end{bmatrix}^T$, $x(t) = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$, and $\eta(t)$ are state variables and its derivative, respectively.

Based on Eq. 5, unknown target maneuver and disturbances are expanded to a new state of the missile-target engagement systems; then, in the next section, we will employ LESO to estimate impact of target maneuvering for designing terminal sliding mode guidance law.

MAIN RESULTS

Linear extended state observer LESO design

As for the time-varying missile-target systems with uncertainties as shown in Eq. 5, a LESO is established in Eq. 6:

$$\begin{aligned} \dot{z}(t) &= Az(t) + Bu(t) + B_1u_1(t) \\ y_1(t) &= Cz(t) \end{aligned} \quad (6)$$

where *z(t)* is state variable and *u1(t)* and *y1(t)* are input and output of observer, respectively. Considering Eqs. 5 and 6, the disturbance estimation error system can be obtained as follows (Eq. 7):

$$\begin{aligned} \dot{e}(t) &= Ae(t) + B_1(u_1(t) - \eta(t)) \\ y_2(t) &= Ce(t) \end{aligned} \tag{7}$$

where $e(t) = z(t) - x(t)$ and $y_2(t) = y_1(t) - y(t)$ are estimation error and output, respectively.
The aim of the proposed observer is to control the input u1(t) such that the estimation error e(t) converges to 0. Due to
the state variables of the original system cannot be directly measured and η(t) is unknown, the state e(t) in Eq. 7 cannot be obtained directly. erefore, in this paper, an output feedback control scheme is constructed for realizing the estimation error can convergent in nite-time.
The output feedback control system is designed as follows (Eq. 8):

$$\begin{aligned} \dot{\zeta}(t) &= A_s\zeta(t) + B_s y_2(t) \\ u_1(t) &= C_s\zeta(t) \end{aligned} \tag{8}$$

where 21 ( ) t R ζ × ∈ is the state variables of the output feedback controller, 2 2 s A R× ∈ , 21 s B R× ∈ , 12 s C R× ∈ are the output feedback controller parameter matrix, respectively.
Considering Eqs. 6–8, the following closed-loop control system of observer can be obtained (Eq. 9):

$$\begin{aligned} \dot{z}(t) &= Az(t) + Bu(t) + B_1C_s(\tau)\zeta(t) \\ \dot{\zeta}(t) &= A_s(\tau)\zeta(t) + B_s(\tau)Cz(t) - B_s(\tau)y(t) \end{aligned} \tag{9}$$

As for the feedback design system Eq. 9, suppose that there exists a real number τ >1 and the parameter matrices (τ) s Aτ , (τ) s Bτ , ( ) s Cτ satisfy $A_s(\tau) = A + B_1C_s - B_sC$, $\lambda_i(A + B_1C_s) = -\tau$, $\lambda_i(A - B_sC) = -\tau$, , then the observer state ( ) z t can convergence the system state ( ) xt , meanwhile such that the estimation error ( ) et can be satis ed with nite-time bounded, i.e., $x_0^T R x_0 \le c_1 \Rightarrow x^T(t)Rx(t) \le c_2, \quad \forall t \in [0 \quad T]$.
Due to space limitations, the proof of this lemma is omitted in this paper, and more details on them can be founded in theorem2 of Yang et al. (2015). e reason lies in that the main purpose of this paper is to propose a simpli ed missile-target model for employing the LESO method into the considered systems. A ther that, based on the obtained results on the feedback control design scheme, an improved sliding mode guidance law for high maneuvering targets will be discussed to improve high-precision interception e ects in next section.

Guidance laws based on SMC method

The key of improving the guidance accuracy lies in how to control the LOS angular rate q by u, such that it approaches 0 to achieve quasi-parallel approach; in other word, to maintain a constant angle of sight between missile and target. Sincethe LOS angular rate cannot be obtained directly, the state observer system output y is selected as the sliding mode surface (Eq. 10):

$$s = y(t) = Cx(t) \tag{10}$$

Due to sign function in the traditional exponential reaching law, the system control quantity is frequently switched near the sliding surface in the process of intercepting the maneuvering target. It brings chattering to the system inevitably and weakens theinterception e ect of the system on high-speed maneuvering targets. In order to reduce the system chattering e ectively and ensure the missile has a high accuracy of hitting, a new sliding-mode exponential reaching law based on the power function is designed (Eq. 11):

$$\dot{s} = -\frac{k|\dot{r}|}{r}s - \frac{\varepsilon}{r} fal(s,\alpha,\delta) \tag{11}$$

where 0 k> , 0 ε> , and (, ,) fal sαδ are the reaching law coe cient, the switching term coe cient and power function, respectively.

The power function is given by (Eq. 12):

$$fal(s,\alpha,\delta) = \begin{cases} |s|^{\alpha} sign(s), & |s| > \delta \\ s/\delta^{1-\alpha}, & |s| \le \delta \end{cases} \tag{12}$$

where and are values between 0 and 1.

This approach law chosen in this paper improves the system control e ect from two aspects:

- Using the power function (, ,) fal sαδ instead of the symbol function term sgn(s), the chattering caused by the sign function in the traditional switching surface is reduced.
- The parameters of the reaching law are adjusted by using the missile-target relative distance r as a dynamic parameter. When is larger, the approach speed is slower. On the contrary, the approach speed is increased rapidly when r is decreased, which ensures the rapid convergence of the LOS angular rate q and improves the missile hit accuracy e ectively.

Considering the system modeling error and the unknown characteristic of the target maneuvering, Eq. 4 is replaced by the designed LESO Eq. 9. It is merely need to ensure that the error Eq. 7 converges to 0 in limited time. From the obtained Eq. 9, thesliding surface is represented as (Eq. 13):

$$s = y_1(t) = Cz(t) \tag{13}$$

Asymptotical stable means that as for the autonomous system x = f (x), suppose that x = 0 is equilibrium point of the autonomous system, if it is stale and there is > 0, such that $\|x(0)\| < \delta \Rightarrow \lim_{t\to\infty} x(t) = 0$.

As for stability of the considered system, the detailed statement is shown in the following. Firstly, based on Lyapunov stability theorem, one Lyapunov function is chosen as (Eq. 15):

$$V(s) = \frac{1}{2}s^T s \tag{15}$$

From calculating the derivation on both sides of Eq. 15 and combining with Eqs. 9, 11–14, obtain

(1) when $|s| > \delta$, $\dot{s} = -\frac{k|\dot{r}|}{r}s - \frac{\varepsilon}{r}|s|^{\alpha} sign(s)$, then (Eq. 16):

$$\dot{V}(s) = s^T\dot{s} = s^T(-\frac{k|\dot{r}|}{r}s - \frac{\varepsilon}{r}|s|^{\alpha} sign(s)) = -\frac{\varepsilon}{r}\|s\|^{\alpha+1} - \frac{k|\dot{r}|}{r}\|s\|^2 < 0 \tag{16}$$

(2) when $|s| \le \delta$, $\dot{s} = -\frac{k|\dot{r}|}{r}s - \frac{\varepsilon}{r}(s/\delta^{1-\alpha})$, then (Eq. 17):

$$\dot{V}(s) = s^T\dot{s} = s^T(-\frac{k|\dot{r}|}{r}s - \frac{\varepsilon}{r\delta^{1-\alpha}}s) = -(\frac{k|\dot{r}|}{r} + \frac{\varepsilon}{r\delta^{1-\alpha}})\|s\|^2 < 0 \tag{17}$$

From Eqs. 16 and 17, we can find both of them are negative definite, therefore, based on the Lyapunov stability theorem, the proposed design scheme for the considered missile systems is guaranteed to be asymptotically stable and meets the design requirements.

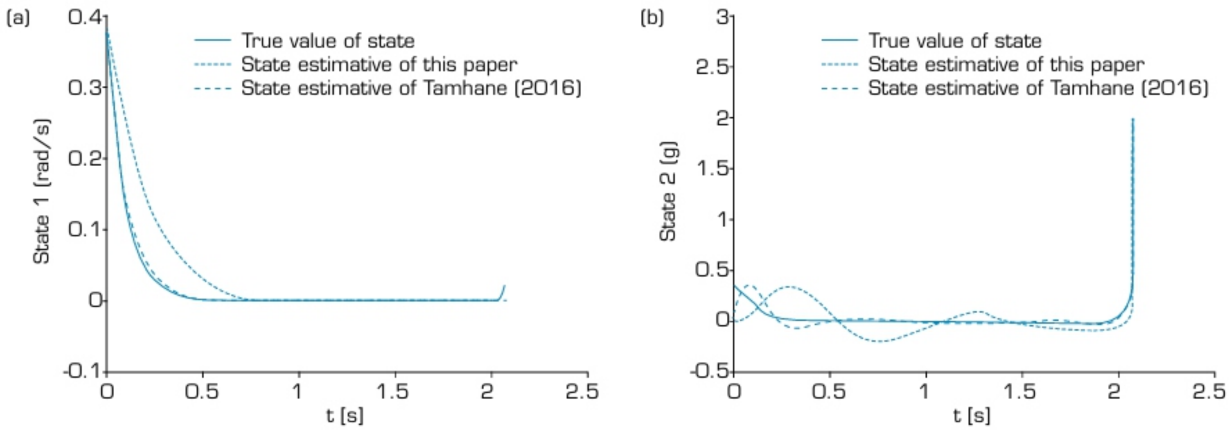
SIMULATION RESULTS AND ANALYSIS

For the systemic model Eq. 4 in the paper, this unknown information, such as the target maneuver and model uncertainties, are expanded to rst-order variables to form a new system, as shown in Eq. 5. It can be seen, from Eq. 5, that the goal of the controller design in this paper is to make the LOS angular rate q close to 0 by solving the control quantity u, so the related items of q in ηt can be ignored.

Consequently, η (t) can be described by $\eta(t) = \frac{\dot{\omega}+\dot{\varepsilon}}{r} - \frac{\dot{r}(\omega+\varepsilon)}{r^2}$. Due to the existence of relative distance r squared term, the second term in η(t) is small, so $\eta(t) \le \frac{\dot{\omega}+\dot{\varepsilon}}{r}$, which is a bounded interval related to r.

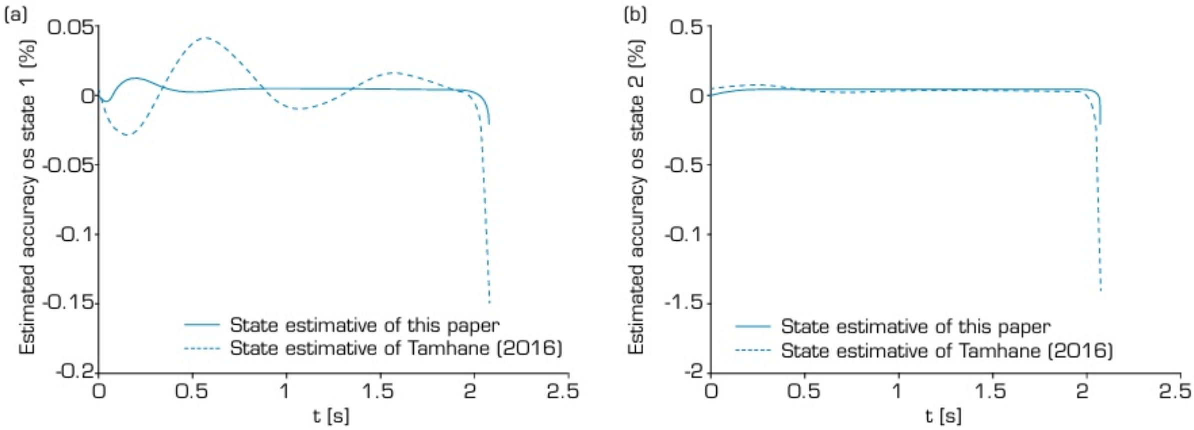
Assume that the target maneuver information is 5 sin(4) g t ω π = , the model uncertainty is 0.5sin(4) t ε π = , and 0.5 r= , finally, then the system model uncertain term x2 and its rate of change η(t) is satisfied with the linearized condition, combining g = 9.8 m/s2, get d = 20.2.

The values chosen for the observer parameter matrix are $B_s = [3\tau \quad 3\tau^2]^T$, $C_s = -[3\tau^2 \quad 3\tau]$, and $A_s(\tau) = A + B_1C_s - B_sC$, respectively, in which the range of observer parameter is 8080 τ≥ when 3 2.5 10 σ − = × is chosen. The initial values of system Eq. 5 state, output feedback controller state, and observer state are selected as [ ] (0) 0.4 0.4T x = , [ ] ( ) 0 0T t ζ = and [ ] ( ) 0.4 0T z t = , respectively. The 5 sin(4) g t π sine signal and 5 (2,) gsquare t square wave signal are used to simulate the target maneuvering conditions; for showing the effectiveness of the proposed method of this paper compared with (Tamhane etal. 2016), the simulations results on state estimation curve and state estimation accuracy curve are shown in Figs. 2 and 3, respectively.



Source: Elaborated by the authors.

Figure 2. System state estimation curve. (a) System state x1 estimated curve; (b) System state x2 estimated curve.

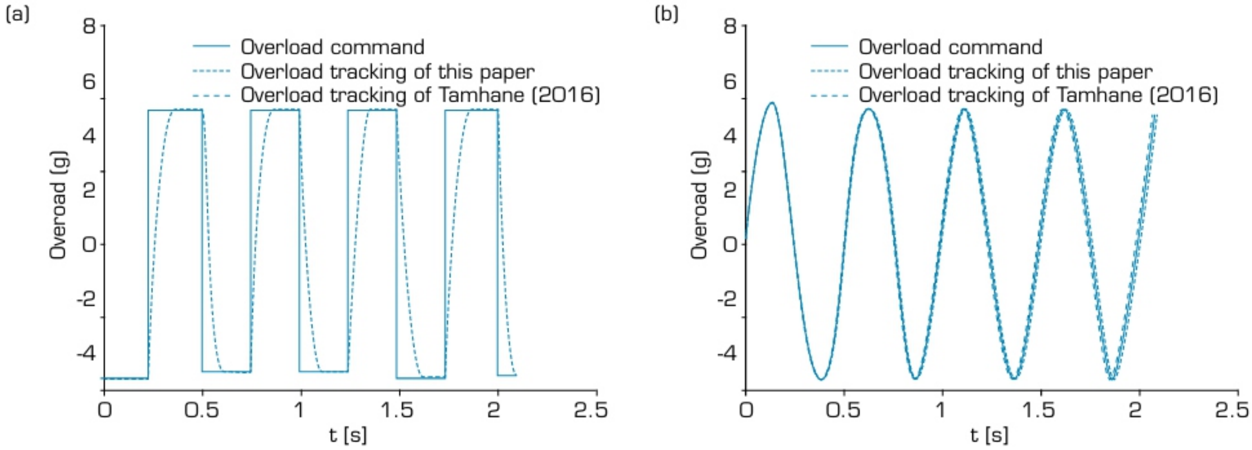


Source: Elaborated by the authors.

Figure 3. System state estimation accuracy curve. (a) System state x1 estimated accuracy curve; (b) System state x2 estimated accuracy curve.

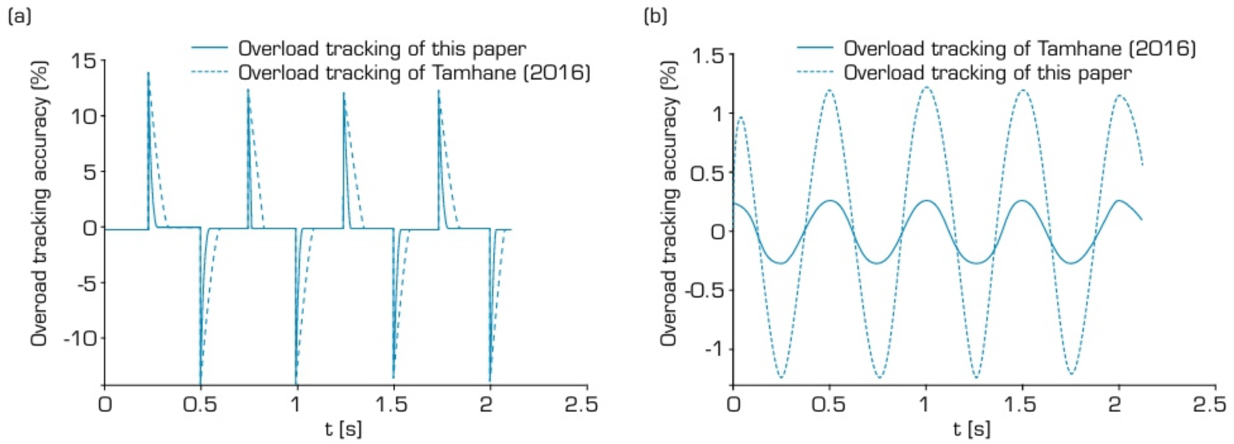
The comparison of the system state estimation is shown in Figs. 2 and 3, in which Figs. 2a and b are the tracking of state x1 and state x2, respectively. Figs. 3a and b show the estimation accuracy curve of state x1 and statex2, respectively. It can be seen from these gures that the LESO designed in this paper not only improves the system state estimation accuracy, but also reduces the time required for convergence to a stable state, which provides a guarantee for successful interception of high maneuvering targets. However, the estimation error of designed observer in Tamhane etal. (2016) has a sudden increase at the end of the guidance, which can be seen from Figs. 2b, 3a and b. is is due to the fact that there is a reciprocal of relative distance r in thesystem state x2. Consequently, the system state approaches innity and the estimation error of observer will increase suddenly when r close to 0. In contrast, the proposed design scheme of this paper has obvious improvement in suppressing the sudden increase of observation error at the end of the guidance. Meanwhile, it veri es the rationality of the controller design using the state estimation value instead of the state actual value.

Another simulation is the estimation of sine maneuvering and square wave maneuvers so as to analyze accuracy of designed observer on the given target acceleration information. The simulation results as shown in Figs. 4 and 5. It can be seen from results that the observation method proposed in this paper has a good estimation e ect on the target of sine and square wave signals as maneuvering information, and the estimation accuracy is improved by nearly three times compared with Tamhane etal. (2016).



Source: Elaborated by the authors

Figure 4. Target maneuver overload estimation curve. (a) Square wave overload estimation; (b) Sine overload estimation.



Source: Elaborated by the authors.

Figure 5. Target maneuver overload estimation accuracy curve. (a) Square wave overload estimation accuracy; (b) Sine overload estimation accuracy.

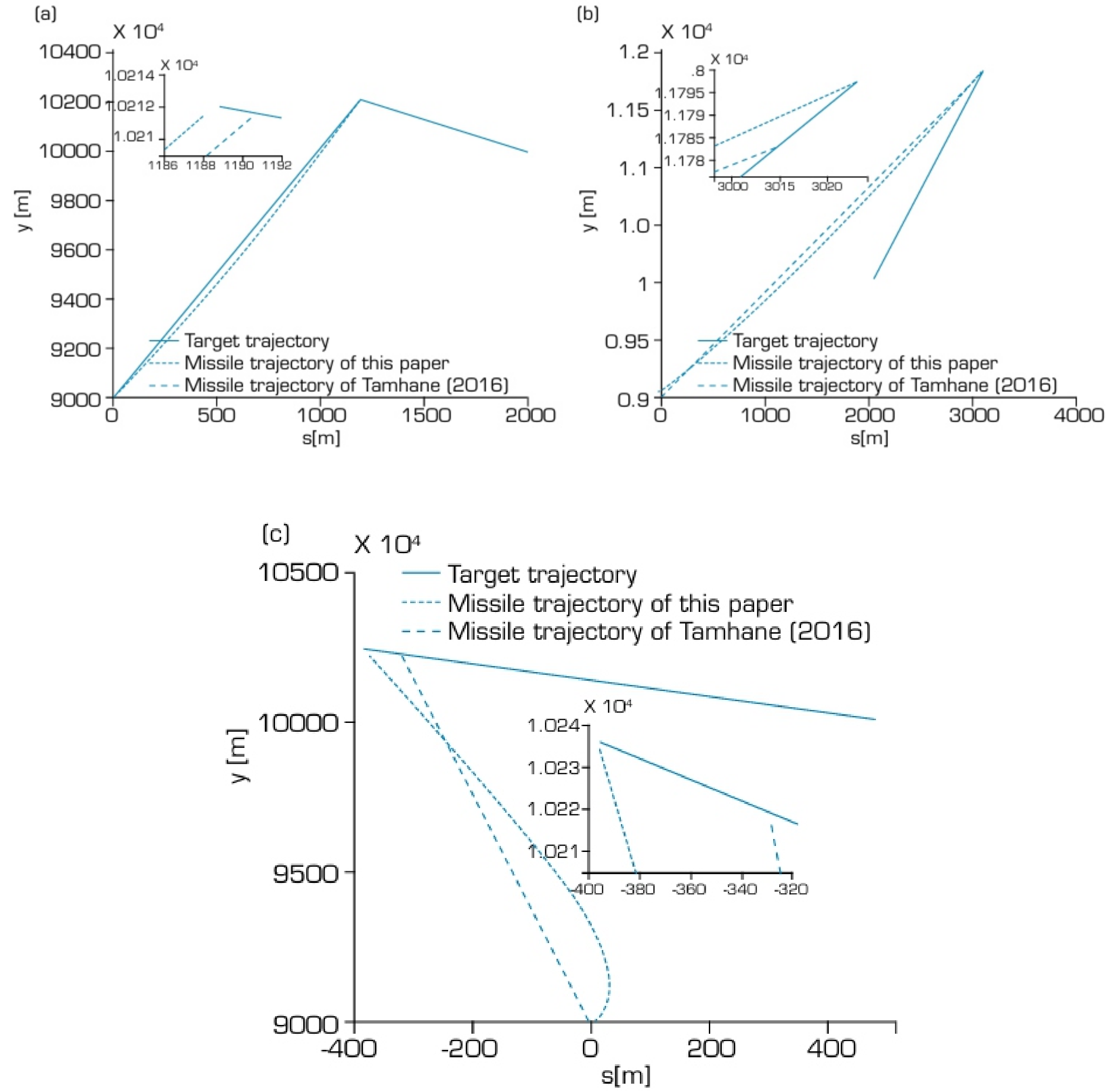
In Zhou (2016) also uses the power law as the reaching law to design the terminal guidance law, the parameters of the SMC are selected as: reaching law coe cient is k = 1.5, coe cient of switch term is = 1.2, the power function parameters are = 0.5 and = 0.01, respectively, missile initial position is (0,9000), ying speed is 600m·s, and the speed direction angle is m = 0. Due to space limitations, this paper only veri es the situation where the target uses 5g sin (4 t) sine signal as maneuvering information. In order to verify the e ectiveness of the interception strategy designed in this paper, three di erent interception methods of attack interception, pursuit interception, and forward interception are respectively compared with the nite-time sliding mode convergence strategy shown in Eq. 11 of Zhang etal. (2015).

- Attack interception: assume that the target ight speed is 400m·s, the initial target speed direction angle is t = 165°, and the target initial position is (2,000, 10,000). The result of simulation comparison is shown in Fig. 6a.
- Pursuit interception: assume that the target fight speed is 400m·s, the initial target speed direction

angle is t = 60°, and the target initial position is (2,000, 10,000). The result of simulation comparison is shown in Fig. 6b.

• Forward interception: assume that the target ight speed is 700m·s, the initial target speed direction angle is t = 165°, and the target initial position is (500, 10,000). e result of simulation comparison is shown in Fig. 6c.

These results obtained are presented in Table 1.



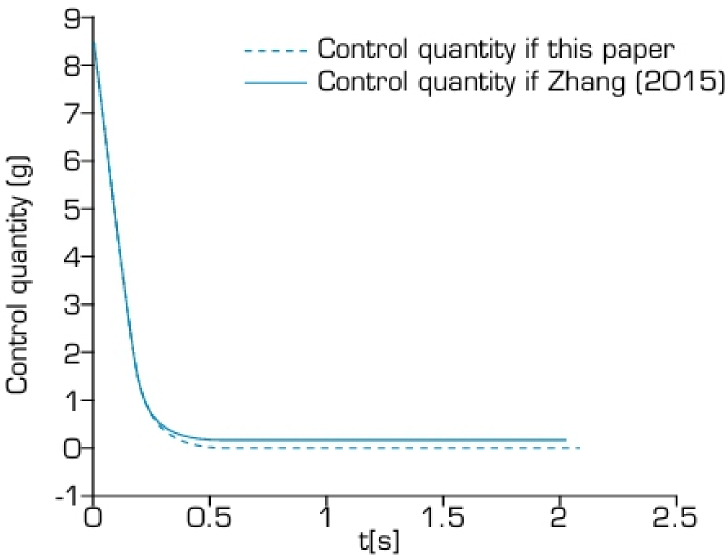
Source: Elaborated by the authors.

Figure 6. Guidance interception curve. (a) Attack interception trajectory; (b) Pursuit interception trajectory; (c) Forward interception trajectory.

Interception way	New sliding mode interception strategy		Finite-time sliding mode convergence strategy	
	Miss distance (m)	Flight time (s)	Miss distance (m)	Flight time (s)
Attack interception	0.489	2.09	1.047	2.11
Pursuit interception	0.536	5.12	1.664	5.27
forward interception	0.956	1.23	1.771	1.33

Source: Elaborated by the authors.

From the simulation results shown in Fig. 6 and Table 1, the proposed new sliding mode interception strategy designed in this paper has improved both in terms of ight time and miss distance. In particular, the size of miss distance can re ect the e ectiveness of the interception strategy directly. In this respect, the e ect achieved in this paper is nearly one time higher than that in Zhang etal. (2015). Fig. 7 shows the comparison of the outputs of the two interception strategy controllers. It can be seen from the gure thatthe control requirements for both interception strategies is relatively large at the initial stage of movement, which is related to the selection of the initial value of system.



Source: Elaborated by the authors.
Figure 7. Controller output comparison curve.

However, the required control of the interception strategy in this paper is smaller. e nite-time sliding mode convergence strategy described in Zhang etal. (2015) during the terminal guidance stage has a certain frequency of chattering. As a comparison of the strategies proposed in this paper, the performance of strategy in the terminal guidance stage is slightly improved, which makes the output of the controller smoother, thus the e ectiveness of improvements made in selection of the approach law is verified.

CONCLUSION

In this paper, a new sliding mode guidance law based on LESO was designed for high maneuvering targets.

• Based on the proposed LESO method, an observer in order to guarantee nite-time convergence was developed to estimate the unknown information online for improving target maneuvers.

• Meanwhile, under the proposed LESO framework, the guidance law of SMC was designed, where the exponential reaching law was improved by the observer state and the relative distance. The extension state increase suddenly at the end of the guidance period by the common reaching law was reduced.

• In addition, the simulation results were given, which con rmed the proposed methods. e accuracy of state observation was increased by nearly two times and the miss distance in almost all cases was reduced by nearly two times compared with the former methods.

In this paper, since the LESO is used to estimate the unknown disturbances, the system is restrained to be linearized due to the LESO assumption. In the future work, a more comprehensive system model should be considered, meanwhile, a nonlinear observer is an important direction for improving higher precision interception.

AUTHORS' CONTRIBUTION

Conceptualization: Tao F, Shi J, Zhang J, Fu Z; Methodology: Tao F, Shi J, Zhang J, Fu Z; Validation: Tao F, Shi J, Song G; Writing - Original Dra : Tao F, Shi J, Zhang J; Writing - Review & Editing: Tao F, Fu Z; Final approval: Tao F.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILTY STATEMENT

Data sharing is not applicable.

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Analysis of the Organization Designation Authorization in Aircraft Certification: Differences to the Brazilian and European Approaches

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A B S T R A C T

This paper aims the identification of the Organization Designation Authorization (ODA) regulatory approaches adopted by the United States, using the Boeing 737 MAX 8 certification process as a basis, by revising the ODA's certification role and what can be enhanced on the ODA program, considering the data from the Federal Aviation Administration (FAA), the U.S. Department of Transportation, AND the Office of Inspector General (OIG), and comparing them to the regulatory basis in Europe and in Brazil. An assessment of undue pressure on ODA Unit members and other aspects, such as conflicting restraints, analysing their consequences and roles for the process' safety, is presented, as well as a comparison with the independent design assurance system adopted by the other two agencies. Therefore, the discussion around the ODA's aircraft certification processes highlights the ODA model drawbacks, and what can be learned from other models to improve it, so the industry and the society can fully benefit from this system.

Keywords: Delegation; Organization Designation Authorization; Aircraft certification; Design organization; Level of involvement.

INTRODUCTION

After the Boeing 737 MAX 8 fatal accidents in 2018 and 2019, questions were raised about the American Federal Aviation Administration (FAA) certification process, especially the delegation process (USA 2020a).

In 2005, FAA created the Organization Designation Authorization (ODA) program through an amendment to 14 CFR Part 183 (FAA 2021b). This regulation defines the requirements for the organizations that want to be recognised as a designee and specifies the authorized functions once the applicant meet all the criteria and have been approved as an ODA (FAA 2011).

In summary, the ODA allows an organization to perform specified functions on behalf of the FAA on subjects related to engineering, manufacturing, operations, airworthiness, and maintenance, according to the FAA Order 8100.15B (FAA 2018).

While, up to now, it is not clear the role of the ODA in those accidents, it is also possible to notice that the delegation approach is not used by Brazilian (ANAC 2021) and European (EASA 2021) authorities, which implemented a different strategy in the certification process performed through design organizations. Therefore, the present paper will evaluate the FAA-ODA process and its differences to the European Union Aviation Safety Agency (EASA) and Brazilian Agência Nacional de Aviação Civil (ANAC) approaches, in order to understand how those differences could influence the certification process of the 737 MAX 8, particularly the overall function of Boeing ODA during this process, analysing the certification process itself, the delegation system and its structure, and the aircraft's development and its non-usual features, such as the Manoeuvring Characteristics Augmentation System (MCAS) and the FAA oversight structure.

METHODS

This paper is an exploratory work, in which an analysis of reports, such as the United States Department of Transportation (U.S. DOT), the Office of the Inspector General (OIG) reports about the development of the 737 MAX 8, surveys conducted by The MITRE Corporation within the FAA, the pertinent regulatory standards from the FAA, EASA, ANAC and the International Civil Aviation Organization (ICAO), other papers and books, is performed.

RESULTS

The Certification Process in U.S.

The U.S. certification process is regulated by the regulations on 14 CFR Part 21 (FAA 2021a) and the guidance is provided by several guidance material, remarkably FAA Orders 8110.48A (2017a) and 8110.4C (2017b). Following these guidelines, section 21.21 of 14 CFR Part 21 (2021a) determines that FAA shall issue a document of approval stating that a specific aircraft model is compliant with applicable regulations, and that no feature or characteristic makes it unsafe for the category in which certification is requested.

Per 14 CFR Part 21 (FAA 2021a), the design approval can address a completely new aircraft design, which requires the emission of a type certificate (TC), or a modification of an approved design, which can be an amendment to the TC (ATC), or a supplemental TC (STC). The first one is applicable only when the change to the TC is made by the TC holder, while the STC can be approved either by the TC holder, or by a third party (FAA 2011). Considering that the case that motivated the questions on the ODA process is a modification performed by the TC holder, the focus of this study will be on the ATC process, and any reference to change or modification of the design will refer to an ATC unless otherwise specified.

The main difference between a TC and an ATC, according to OIG (2021), is that under the ATC only areas that present significant changes in design need to be brought up to current airworthiness requirements, following the section 21.101 of the 14 CFR Part 21 (FAA 2021a), the changed product rule. There are, nonetheless, exceptions that can be applied and the applicant can comply with earlier requirements if, according to section 21.101 of the 14 CFR Part 21, an area, system, component, equipment, or appliance are not affected by the change, if compliance with a later amendment does not materially improve safety, or if compliance with the latest amendment is impractical.

Another aspect established by the section 21.101 of the 14 CFR Part 21 is the time span of five years to complete the certification process from the moment the applicant files for the ATC (FAA 2021a). If the design is approved during this time range, the applicant must comply with the airworthiness requirement in effect on the date of the application for the change, and with the environment protection regulations.

The FAA ODA Program

As described before, in 2005, FAA (2021b) created the ODA program through an amendment to 14 CFR Part 183 to standardize and consolidate these delegations under a single initiative for manufacturers of a product or articles produced under a TC.

Through the ODA, FAA may delegate a substantial amount of critical work during the certification process, respecting the assumptions on 49 U.S.C. 44702(d) (USA 2020b), a legislation that specifies the issuance of certificates, and have suffered two amendments after its introduction in 1958, with the latest and most relevant amendment made in 2020, after the Boeing 737 MAX crashes. This last amendment determines that the FAA may not delegate any finding of compliance with applicable airworthiness standards or review of any system safety assessment required for the issuance of a certificate, including a TC, or amended or STC, until the FAA has reviewed and approved all assumptions related to human factors.

According to DOT (USA 2020a) the concept of delegation has been promoted for decades by the U.S. Congress, which encouraged its expansion on the 2012 and 2018 FAA Reauthorization Acts.

Also, as per the FAA Order 8100.15B (2018), ODA is the authorization to perform a variety of previously approved functions on behalf of the FAA, while ODA Holder is the organization that obtains this authorization from the FAA through a Letter of Designation, and finally, an ODA Unit is an identifiable group of two or more individuals within the ODA Holder's organization that apply and perform the previously authorized functions following the FAA Order 8100.15B.

To be able to get an ODA, the organization must submit an application to the FAA, containing the functions for which the authorization is being requested, the qualifications of the applicant, such as proof of sufficient resources, personnel, facilities, and relevant experience to correctly perform the pledged functions, and also have previous and vast experience with FAA requirements, processes and procedures (FAA 2017c).

According to the 14 CFR Part 183 (FAA 2021b), the applicant must have a description of their organizational structure and a proposed ODA Unit within its existing structure, as well as a proposed procedures manual, containing the functions and limitations authorized by the FAA and the procedures for performing those functions. It must also contain an organizational structure and the responsibilities of the ODA Unit and the ODA Holder, as well as a description of the infrastructure and facilities used by them.

The manual must also underline the training requirements for ODA Unit personnel, a process and a procedure of an ODA Unit periodic audit by the ODA Holder in compliance with FAA's regulatory material, which must be acquired and maintained by the ODA Holder.

Furthermore, FAA (2017c) states that the manual must have a description of the experience required and knowledge required each position within the ODA Unit, procedures for revising the manual and procedures for performing the activities for product certification and operational approvals. After the process approval by the FAA, according to the 14 CFR Part 183 (2021b), the ODA Holder receives its Letter of Designation, and must comply with the procedures contained in its approved procedures manual in order to maintain the effectiveness of the Letter of Designation, which can be revoked sooner by the FAA if the ODA Holder requests its termination or suspension before the due date, or if the Holder has not performed its duties properly and no longer meets the qualifications required to perform the authorized functions that have been previously authorized by the FAA.

For any approval or certificate for a product, part or appliance the ODA Holder must monitor reported service problems related to certificates or approvals and notify the FAA if a product, part or appliance has a condition that could result to be unsafe, or another one that does not meet the applicable airworthiness requirements, according to the 14 CFR Part 183 (FAA 2021b). The FAA can demand an investigation to the ODA Holder to find any suspected unsafe condition or after the discovery of noncompliance with the airworthiness requirements, producing the information necessary to implement corrective actions to end with the nonconformities, with all data submitted to the FAA at the end of the process.

The ODA goal, according to DOT (USA 2020a, p. 22), is:
The structured, safety-focused delegation system bolsters aviation safety and encourages innovation, efficiency, and industry growth. Delegation processes, including ODA, provide space for innovation and technical expertise while enabling the FAA to maintain its oversight processes and maintain established safety standards. By making use of delegation, the FAA is able to use a risk-based approach to focus its attention on the most critical certification areas.

The EASA DOA

The Design Organisation Approval (DOA) program is established by EASA under Part 21 Subpart J, of the Commission Regulation (EU) No. 748/2012, which standardizes the rules for airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as the certification of design and production organizations. The program was developed to establish a designee program, especially an organization, just as its counterpart program in the U.S. In terms of application, however, some things differ from the FAA program. At first, the applicant may fill a handbook provided by EASA with all the data necessary, such as the company's organizational structure, information about the procedures adopted in the product development, the assurance of compliance, establishing a design assurance system for the control and supervision of the design, changes in design, products, parts and appliances.

This handbook must be handed to the agency, as well as any amendment necessary to keep it up to date to any changes in the company. The design organization must also state the management staff qualifications and experience as well as the qualifications of those who are linked to any decision that affects airworthiness and environmental issues in the organization (EASA 2021).
Once every aspect discussed previously have been scrutinized by the authority, an unlimited duration design organization approval is issued stating the specific terms of approval, such as the types of design work, the categories of products, parts and appliances for which the design organization holds a design organization approval. For DOA continued validity the holder must be able to demonstrate compliance with all the applicable requirements under EASA Part 21 Subpart J, the agency must be able to perform any investigation, including investigations of partners and subcontractors, and the holder must allow the agency to make any inspection, review any report and perform any test necessary to check the validity of the compliance statements made by the holder during the certification process. The design assurance system must also maintain a satisfactory control and supervision of the changes and the design of products, for the limitless duration of the approval to continue. The EASA can also revoke any certificate under applicable administrative procedures at any time (EASA 2021).

Any non-compliance with the applicable requirements under EASA Part 21 of a DOA holder found during an investigation are categorized in three distinct levels: A level one finding is any non-compliance which could affect the safety of the aircraft and which could lead to uncontrolled non-compliances with applicable requirements, the holder has no more than 21 working days to demonstrate necessary corrective action to fulfil the agency's needs. A level two finding is any non-compliance which is not classified as level one, the corrective action period granted by EASA must not exceed three months at first; however, in certain circumstances, this period can be extended by the agency until a satisfactory corrective action plan is presented. A level three finding is anything that has been identified by direct evidence, to contain potential problems that could lead to a non-compliance, and it does not require immediate action by the designee. In case of levels one and two findings, the design organisation approval can be partial or fully suspended or revoked (EASA 2021).

During the certification process the DOA holder is entitled to perform activities within its scope of approval. Following the compliance documents, the approval of flight conditions for a permit to fly, a type-certificate or approval of a major change to a type design, a supplemental type- certificate, as well as a major repair design approval can be accepted by EASA without further verification, but can be thoroughly investigated by the agency if it judges to be necessary. The holder is also entitled to classify any changes to type design and repairs as major or minor, to approve minor changes to type design, minor repairs and the design of major repairs to products or auxiliary power units for which it holds a European Technical Standard Order (ETSO) authorization, a type-certificate or a supplemental type-certificate, to approve the conditions under which a permit to fly, related to the safety of the design, can be issued. The designee can also approve minor revisions to the aircraft flight manual and supplements, and publish instructions or information issuing statements standardized by EASA (2021).

Furthermore, the holder of a design organization approval must maintain its handbook in conformity with the design assurance system and ensure that it is used as a basic working document within the organization. The designee must provide EASA with statements and the necessary documentation to confirm the compliance with the requirements of the design of products, changes or repairs, and provide the required information or instructions related to airworthiness directives. Finally, the organization must determine the conditions under which a permit to fly can be issued, establishing compliance with the agency's requirements (EASA 2021).

The ANAC COPj

ANAC implemented a Certified Design Organization in the amendment 3 of its Brazilian Civil Aviation Regulations (RBAC) 21 regulation known as COPj (ANAC 2018; 2021). The approach used by Brazilian authority is similar to the European one, however, differently from EASA, the organization certification is not a condition to obtain a TC. Therefore, the TC Holder, in Brazil, could be a certified organization, with a design assurance system, or a person that demonstrates a product complies with applicable regulations (ANAC 2021).

Another crucial point is that, even considering the RBAC 21 adopted a similar requirement to EASA, the European regulation already implemented changes that were not absorbed by Brazilian RBAC yet, such as the privileges of the organization and, therefore, it is possible that differences could exist between a design organization in each country (ANAC 2021). However, for the differences raised above with FAA approach, ANAC strategy can be considered identical to European one, with the certification of the organization instead the delegation of authority.

Differences between ODA and DOA

Both agencies have differences when issuing design approvals, especially with the type of information transferred to the authority by the designee, as well as some specific bureaucracies for the issuing of the certificate of designation and the certification itself.

A difference between the FAA and EASA designee programs is the approval of operational requirements, while the FAA certification process includes only the requirements for the approval of the aircraft design; in other words, the operational requirements can be met after the issuing of a TC, but before the entry into service. The EASA certification process is a little bit different from its counterpart, the compliance with the operational requirements and standards must be entirely fulfilled prior to the issuance of a TC (De Florio 2016).

While there are a lot of similarities between both approaches, there is a core difference: the ODA is a delegated structure inside the design organization, i.e., it is a system that acts on behalf of FAA (Yang and Liu 2011). Therefore, the ODA will perform the same activities of the FAA, which means that they will verify the compliance with the requirement based on a determined level of involvement, which specify what verifications tasks will be performed directly by FAA employee, the ones that will be performed by ODA unit member, and the ones that will not require a verification. This verification, performed under paragraph 21.33(a) of 14 CFR Part 21 (FAA 2021a), is a second layer to identify failures in the show compliance performed by the design organization (GAO 2022).

On the other hand, the independent Design Assurance System (DAS) from EASA DOA is a more embracing system, where the verification is only one part of the certified system, with the DAS also covering the development and show compliance processes. Furthermore, it is important to notice two differences to ODA verification: The DOA verification is performed over all show compliance data and artifacts, instead only a part as in FAA ODA; and the verification part of the DAS is performed using processes established by the DOA, that are adequate for their environment and are responsive to the independent monitoring findings, while ODA must follow the same processes and documents that FAA employees use (GAO 2022).

The aforementioned difference is clearer when we evaluate the self-monitoring of both system: while FAA ODA self-audit is focused on the ODA activities (i.e., only in the verification), the EASA DOA independent monitoring system cover all the certification process (GAO 2022).

Moreover, under EASA DOA, the design organization is responsible for all certification compliance findings, that is certified to perform these tasks, what is important to create the sense of accountability on the design organization. Otherwise, the FAA ODA, as stated above, must perform its activities as delegated by FAA, what could undermine this sense of accountability (GAO 2022).

Therefore, there are some points that need to be improved on the ODA program, and they will be further analysed on the next chapters.

CASE STUDY

Current Boeing ODA Unit

Currently, the Boeing 737 MAX and 777X certification programs use the ODA system, employing guidelines to appoint and evaluate ODA Unit members, and following the FAA-approved Boeing Commercial Airplanes ODA Procedures Manual. In 2020, Boeing had 1399 ODA Unit Members, 1004 assigned to engineering and 395 assigned to manufacturing (USA 2020a). These Unit members are Boeing employees from areas such as engineering, and production, that act on FAA's behalf while performing ODA functions during the certification process. This structure is supervised by the FAA's Boeing Aviation Safety Oversight Office (BASOO).

BASOO is part of AIR's System Oversight Division (AIR-800) and is based in the Seattle area. It oversees large-scale inspections, routine audits and oversight, as well as participating in flight tests, ground tests, inspections and test witnessing.

737 MAX Development

On January 27, 2012, Boeing officially filed an ATC application for the 737 MAX 8 with FAA. This milestone marks the beginning of the aircraft's certification process.

The proposed certification basis for the Boeing 737 MAX 8 followed the requirements in the section 21.101 of the 14 CFR Part 21 (FAA 2021a), the changed product rule, using the guidelines within AC 21.101-1B (FAA 2016) and Order 8110.48A (FAA 2017a).

Following the requirements established by this regulation, the certification basis was defined, and Boeing identified 12 changes labelled as significant from the Boeing 737-800, that was used as the baseline model for the Boeing 737 MAX 8. Among these modifications, there was a crucial addition to the aircraft systems, the MCAS, which was needed to compensate for aerodynamic changes from the baseline model, due to its larger, heavier engines and their placements on the wing.

This system would later be a pivot of a crisis within the 737 MAX program and would put in doubt the credibility of the FAA certification process, especially the delegation program (OIG 2021).

ODA level of involvement during the 737 MAX certification process

According to U.S. DOT (USA 2020a), the FAA determined which areas of the Boeing 737 MAX 8 would be involved, via delegation or directly, through a risk-based decision approach, establishing a risk assessment process that was both quantitative and qualitative, by analysing elements such as historical operational data derived from the baseline aircraft, the standard practices regarding maintenance, regulation criticality and standard operational practices intended to maintain a compliant product.

From February 15, 2013 to November 14, 2013, the FAA reviewed and accepted the Master Certification Plan, which described the acceptable means of compliance during the certification process, which items would be delegated to the ODA and which items and areas would remain under the FAA. After the initial approval, the FAA had retained the sections related to the stabilizer, including MCAS, and the flight controls.

The FAA level of involvement during the certification is at the Agency's discretion at any given moment during the program and based on a risk assessment (USA 2020a). In some cases, the FAA may choose to leverage applicant expertise to aid on critical areas. This, however, is defined after a proper risk assessment of the information provided by the applicant. The U.S. DOT (USA 2020a) also stress the importance of FAA level of oversight, and its confidence in an organization that propitiates a higher quantity of delegations to the manufacturer's ODA.

Furthermore, OIG (2021, p. 25) states that, during the 737 MAX 8 certification program,

Notably, the number of certification activities that FAA delegated increased significantly throughout the certification process, which, according to FAA managers, is typical as systems mature and the Agency gains confidence in Boeing's capabilities through its initial involvement.

Initially, only 28 out of 87 (32%) of the detailed certification activities were delegated to the Boeing ODA for approval. This number, however, eventually reached 79 out of 91 (87%) by November 2016, including the system revisions, containing MCAS, and the flight controls modifications, sections of the Master Certification Plan originally retained by FAA. Moreover, as stated by OIG (2021, p. 26):

FAA can delegate specific deliverables within each certification plan, such as system safety assessments, even if FAA retains the plan itself. These delegations can also change over the course of the

project, as was the case for the over 1,700 Boeing 737 MAX deliverables.
However, in 2015, OIG (2015) reported a concern about the FAA's lack of a risk-based oversight approach to ODA. This was ratified when FAA identified some problems regarding the quality of ODA certification documents that needed to be undertaken, as well as violations of Boeing's document control system, and insufficient certification documents. By December of that year, Boeing was condemned to pay a civil penalty of US$ 12 million due to these transgressions.
According to OIG (2021), later oversight encountered indications that Boeing did not comply with all affairs raised by the FAA. Another issue identified by Boeing and FAA was reported undue pressure on ODA personnel at multiple Boeing facilities, leading to a formal compliance action against Boeing issued by the FAA in November 2018, these predicaments will be detailed at the following section.

Possible Failures of Boeing ODA System

The section 183.57 of the 14 CFR 183 (FAA 2021b) requires ODA companies to grant ODA Unit members sufficient authority to perform their authorized duties, without any interference that affect the member's performance to deal with ODA functions and not give any conflicting non-ODA assignments.
A thriving ODA, according to FAA Order 8100.15B (2018), is an ODA which provides the necessary authority and time to each Unit member, without influence or pressure from other branches of the organization. This later description outlines what is known as undue pressure.

Another recurrent issue addressed by FAA Order 8100.15B (2018) is the necessity of no conflicting restraints or responsibilities for the members that conflicts with the ones from the ODA Unit. This, however, is not extensively explored by the regulations, with the definition of conflicting restraints becoming vague, and it does not specifically impede an engineer to both demonstrate and then evaluate compliance on the same design.

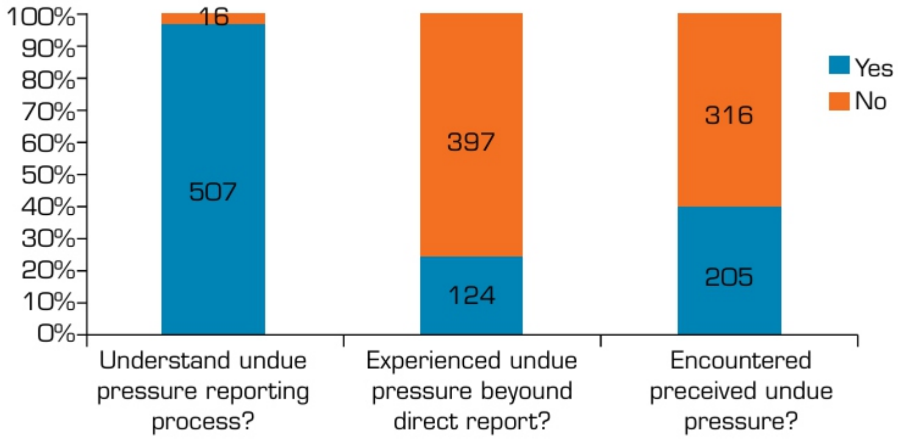
According to OIG (2021), during interviews with FAA and Boeing ODA, they confirmed that there were cases during the Boeing 737 MAX 8 certification that the same company engineer worked on a particular design and then approved it as an ODA Unit member, as employees are only considered ODA Unit members when they are performing tasks on FAA's behalf. OIG (2021, p. 36) states that this situation "may not provide enough independence and could cause a conflict of duties for those Unit members."
A survey conducted by MITRE (2020a) from November 20 to December 9, 2019 with FAA employees under the FAA Office of Aviation Safety (AVS), including the staff from the FAA Aircraft Certification Service, indicated that more than 40% of the respondents did not feel the FAA appropriately delegated certification activities to organizations and individual designees.
Another issue identified in survey responses was the difficulty of the FAA AVS to deal with influences of industry, lobbyists and other political pressures. There were some concerns raised, such as the organization's tendency to put profit over safety, external influence and a too close a relationship with industry.

With the FAA proposing two civil penalties against Boeing and two separate letters of investigation, issued in June 2019 and March 2020 against Boeing's South Carolina facility, detailing work interference and undue pressure of ODA Unit members by Boeing management. Penalties totalled $1.25 million (MITRE 2020b).
FAA and ODA holders are aware of such safety concerns derived from undue pressure on the ODA Unit members. The section 183.53 of the 14 CFR Part 183 (FAA 2021b) requires ODAs to establish and

include in their procedures manuals processes for preventing interference, including performing periodic self-audits of every aspect of the ODA Unit, from the staff to processes, policies and compliance with ODA regulations. These self- audits are valuable, and, according to OIG (2021), both Boeing ODA and FAA have identified instances of potential undue pressure on Unit members from at least 2013.

Over the course of 2013 to 2019, the Boeing ODA found concerns regarding undue pressure on eight of eleven self-audits conducted at Boeing facilities in South Carolina and Washington. For OIG (2021), although none of the audits found violations of FAA regulations and Unit members were confident using the undue pressure reporting process, there were reports that members lacked the confidence that this process could reach a satisfactory conclusion or even protect the Unit members, and the perception of inadequate protection from actions by leadership outside of ODA.

Furthermore, in 2016, an undue pressure survey of the Boeing ODA Unit was conducted by the company, as seen in Fig. 1. There were 523 respondents, and while 97% of them understood the process for reporting undue pressure, close to 40% responded that they had encountered situations in which they perceived undue pressure, and almost 25% had experienced undue pressure beyond their direct reporting structure while performing ODA duties.



Source: Retrieved from OIG (2021, p. 36).
Figure 1. Results of Boeing's 2016 Survey on ODA Undue Pressure.

Reports of pressure from high workloads, potential undue pressure due to the dual role of a Unit member, confusion and the desire for shared information about other cases of undue pressure within the company to help other Unit members learn from them were common during the survey. One respondent claimed that while: "upper management will never issue a direct order for [a Unit member] to do the wrong thing, [they] will create situations to indirectly pressure the [Unit member] to do the wrong thing" (OIG 2021, p. 39).

After this 2016 survey, Boeing addressed all formally reported cases of undue pressure without FAA action. However, the Agency observed the necessity of further oversight of the undue pressure systems and processes. In 2018, five engineering Unit members reported instances of interference or conflicting duties with their Unit member roles. This led to a formal compliance action against Boeing by the FAA, arriving in 2020.

The formal responses to FAA's enforcement actions and results from Boeing's 2016 internal survey provided a variety of causes for undue pressure, such as schedule pressure, which comes to the surface due to cost concerns, lack of knowledge from the Boeing management about their ODA roles, lack of communication between Unit members and ODA management, the delineation of company and ODA roles. That could lead to a pressure on the Boeing ODA Unit member to approve items or confirm compliance with regulations without the proper time to perform a review, acting against their own judgement and expertise, potentially impacting the aircraft safety (OIG 2021).

Moreover, the FAA AVS employees expressed their perception about external pressure for MITRE (2020b), feeling an intense pressure by industry to meet their production deadlines, as well as the way the industry perceives AVS employees and ODA Unit members to be standing in the way, and escalating it to senior leadership and even the Congress, resulting on the reversal of staff engineering recommendations and the replacement of individuals, for example.
Another source of pressure, according to MITRE (2020b), is the unwritten code to be more liberal-minded, supported by the Congress, FAA senior leadership and the industry, in terms of safety/risk, to find win-win solutions that benefit industry, putting pressure on technical staff that are responsible for identifying safety issues and concerns.

Other common worry identified by MITRE (2020b) was the concern that the FAA has delegated too much authority to industry, under 49 U.S.C. 44702(d), negatively affecting the safety of the National Airspace. According to employees overheard by MITRE (2020b), the current delegation system and ODA Model are causing FAA to move away from its safety mission, as well as creating confusion about FAA's role as a regulator and as a promoter of safety.
For MITRE (2020b), the ODA System relies on the safety mindset and culture of the designees, and when they are compromised or inadequate, the system becomes compromised and less effective.

Boeing ODA and the MCAS
In 2016, less than a year before the end of certification, a Boeing ODA Unit member advisor expressed, in an internal email, his concerns regarding a lack of clarity by Boeing when notifying FAA about changes made late in the certification process, as well as its lack of confidence that FAA and ODA Unit members clearly understood, after the flight-testing certification campaign started, what they were approving when Boeing made changes during this period (OIG 2020).

In May 2016, Boeing introduced the MCAS Revision D, and while mentioning some aspects about the system during a briefing with FAA flight test personnel, such as the increased maximum range of the horizontal stabilizer movement under MCAS from 0.55° to 2.5° and the changed parameters that permitted MCAS to be activated at much slower airspeeds than before, ranging from 0.2 to 0.84 Mach, whereas previously it could only be activated at speeds above 0.67 Mach, the FAA certification engineers were unaware of the significant changes to this system and did not correctly understand how it worked (OIG 2021).

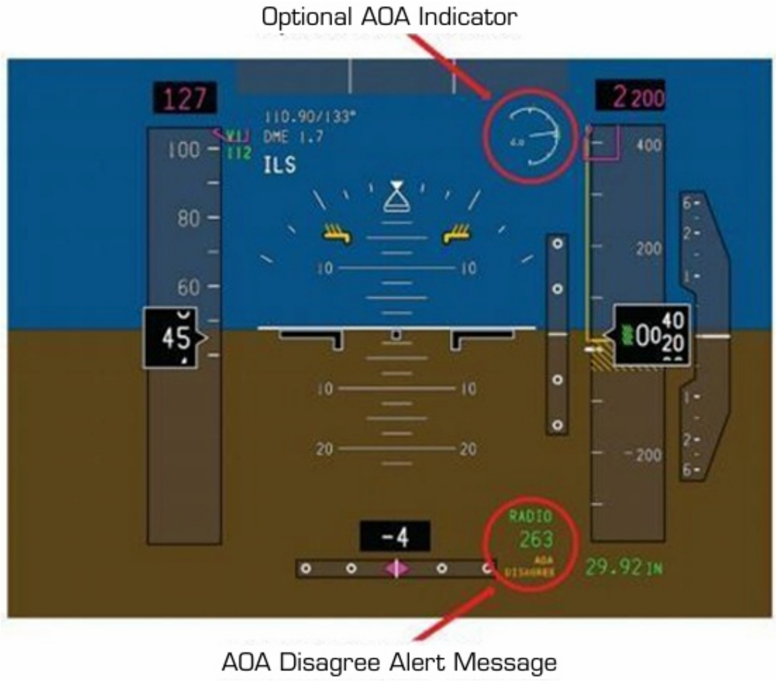
There were multiple FAA branches, groups, divisions and offices involved in the certification process, specifically employees from the Aircraft Certification Service and the Flight Standards Service with its Aircraft Evaluation Group (AEG).
The AEG was responsible to determine the appropriate type rating and levels of pilot training required for the 737 MAX 8 aircraft, and, according to OIG (2020), the inspectors were also unaware of the

MCAS full capabilities. As a result, they were making vital decisions regarding the information provided to pilots without fully understanding the function, like approving the complete remotion of any mention of MCAS from flight crew manuals in 2016. An AEG employee that was responsible for approving the change stated that: “FAA, as a result of the information they had at the time, based the decision on the understanding that MCAS remained as originally designed” (OIG 2021, p. 22).

Furthermore, Boeing’s objective to keep the same type rating as the 737 NG, and to keep costs down by bypassing simulator training for 737 MAX pilots, according to OIG (2021, p. 22), led to: “internal messages discussed how Boeing wanted to present it to FAA as an additional function of the existing speed trim system, as well as its ODA’s concurrence with that approach, while still using the term ‘MCAS’ internally.” By using this approach, the MCAS was not an area of emphasis regarding pilot training, which was more focused at the new flight displays and banking warnings.

While Boeing tested a single, inadvertent activation of MCAS, multiple activations were not tested, assuming that repeated activations of MCAS would not be worse than a single activation. When developing the risk assessment, Boeing engineers and test pilots made an engineering assumption that commercial pilots would react to an unintended MCAS activation as a runaway stabilizer event (OIG 2021).

In addition, even after the 737 MAX 8 certification there were communication gaps between Boeing and FAA. In August 2017, Boeing became aware that not all 737 MAX 8 were equipped with an AOA disagree alert, as seen in Fig. 2, to notify pilots when the two AOA sensors disagree by more than 10° for at least 10 s.
Boeing later included the AOA disagree alert message in updated certification documents, that were approved by a Boeing ODA Unit member in September 2017. According to OIG (2020), the company considered that this modification would not have an operational impact, and did not submit a formal notification to the FAA oversight office. FAA was only officially notified by Boeing about this issue after the Lion Air accident.



Source: Retrieved from OIG (2020, p. 28).
Figure 2. AOA Disagree Message and AOA Indicator.

CONCLUSION

The regulations of counterpart programs in Europe and Brazil, which have a more embracing system, could be used as an example to strengthen the regulatory basis of the ODA program. The independence assured by both regulations, as well as the clear separation of roles provided by the organization certification approach are a step forward to the ODA program, and should be considered by FAA to consolidate its regulatory basis, and properly address the conflicting restraints issues.

Therefore, the ODA model adopted for the Boeing ODA during the Boeing 737 MAX 8 certification requires some important enhancements, and while changes are necessary for an overall improvement on the certification process, the separation of roles, the effective determination of the authority's involvement and the definition of the accountability and liability of the ODA Holder are key factors, combined with improvements on the dialog with FAA, to enhance safety.

Finally, this paper described different approaches to certification, using the 737 MAX 8 certification program and the FAA, EASA and ANAC regulatory basis, analysing the possible failures occurred during this process and what could be optimized and improved on the ODA program, while evaluating the proposed changes to the program.

AUTHORS' CONTRIBUTIONS

Conceptualization: Winkeler BB and Oliveira MVR; Methodology: Winkeler BB and Oliveira MVR; Software: Winkeler BB and Oliveira MVR; Validation: Oliveira MVR and de Andrade D; Formal analysis: de Andrade D; Investigation: Winkeler BB; Resources: Winkeler BB and Oliveira MVR; Data Curation: Winkeler BB; Writing - Original Draft: Winkeler BB; Writing - Review & Editing: Winkeler BB, Oliveira MVR and de Andrade D; Visualization: Winkeler BB and Oliveira MVR; Supervision: Oliveira MVR and de Andrade D; Project administration: Winkeler BB.

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